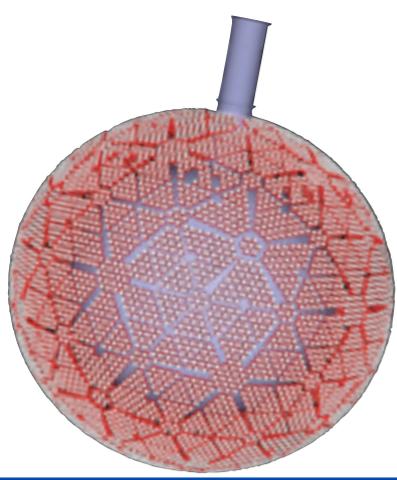




SNO, SNO+ & THEIA

Gabriel D. Orebi Gann



Berkeley Group

NSD Supported

Joint LBNL NSD Staff / UC Berkeley Faculty

G. D. Orebi Gann

Other Support

Post Docs

Javier Caravaca (*DOE ECA*)

Freija Descamps (*DOE ECA*)

Cécile Kéfélian (*Breakthrough Prize Fund, SNO, Oct 31 start*)

Richie Bonventre

(*40% FTE, startup*)

Graduate Students

Ben Land (*UCB startup*)

Chris Benson (*UCB startup*)

Jeff Prouty (*NSSC fellowship*)

<Peter Madigan> (*1st year*)

Undergraduate Students

Joe Singh

Jordan Sullivan

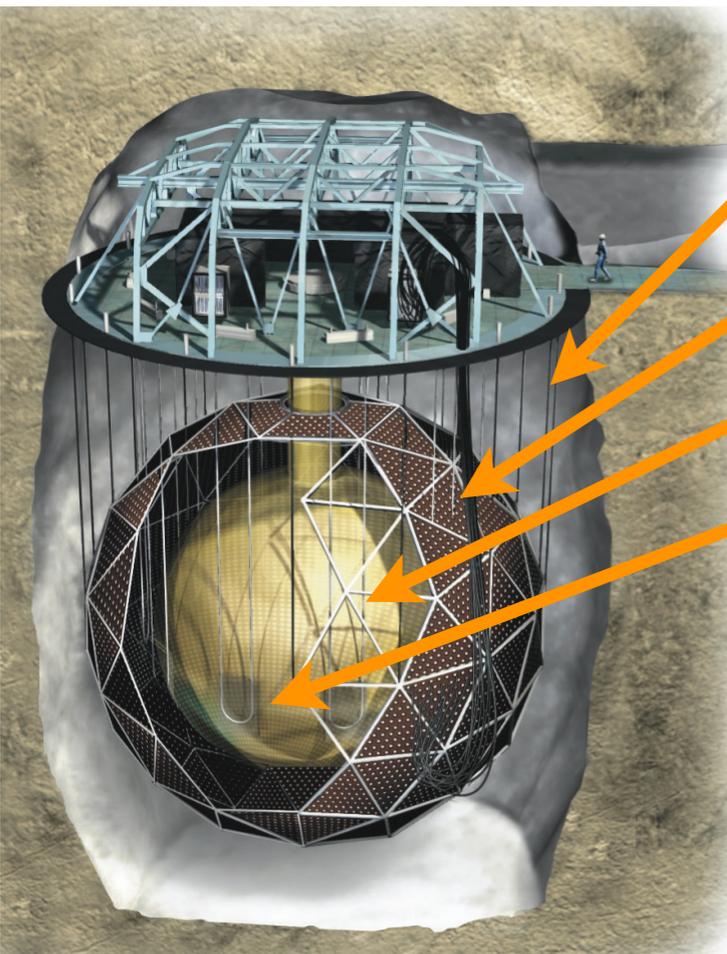
Alumni

Post Docs

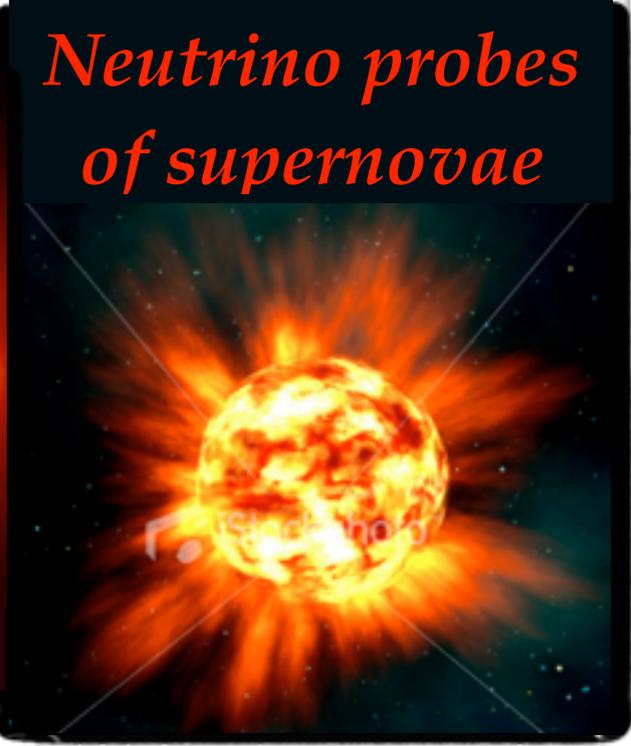
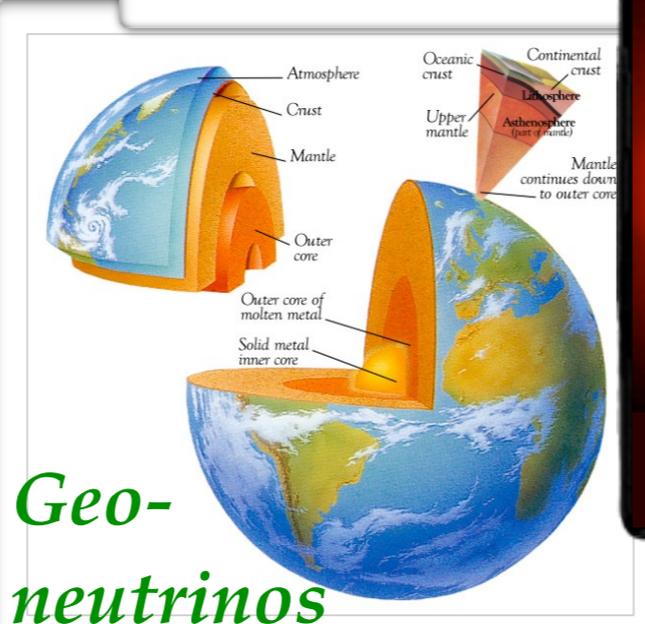
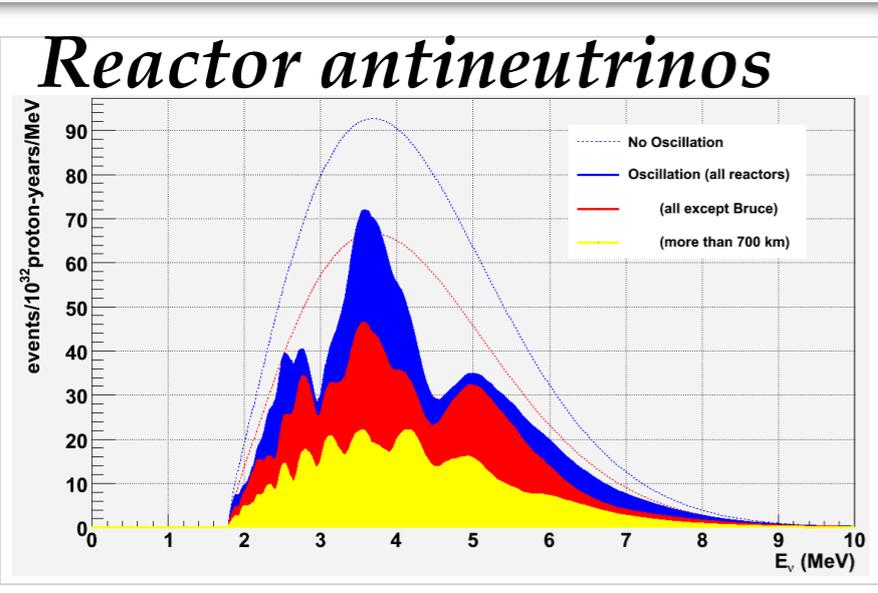
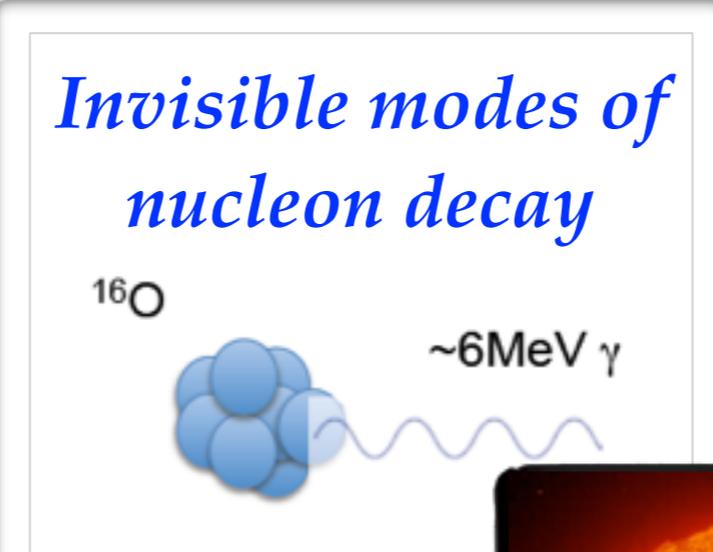
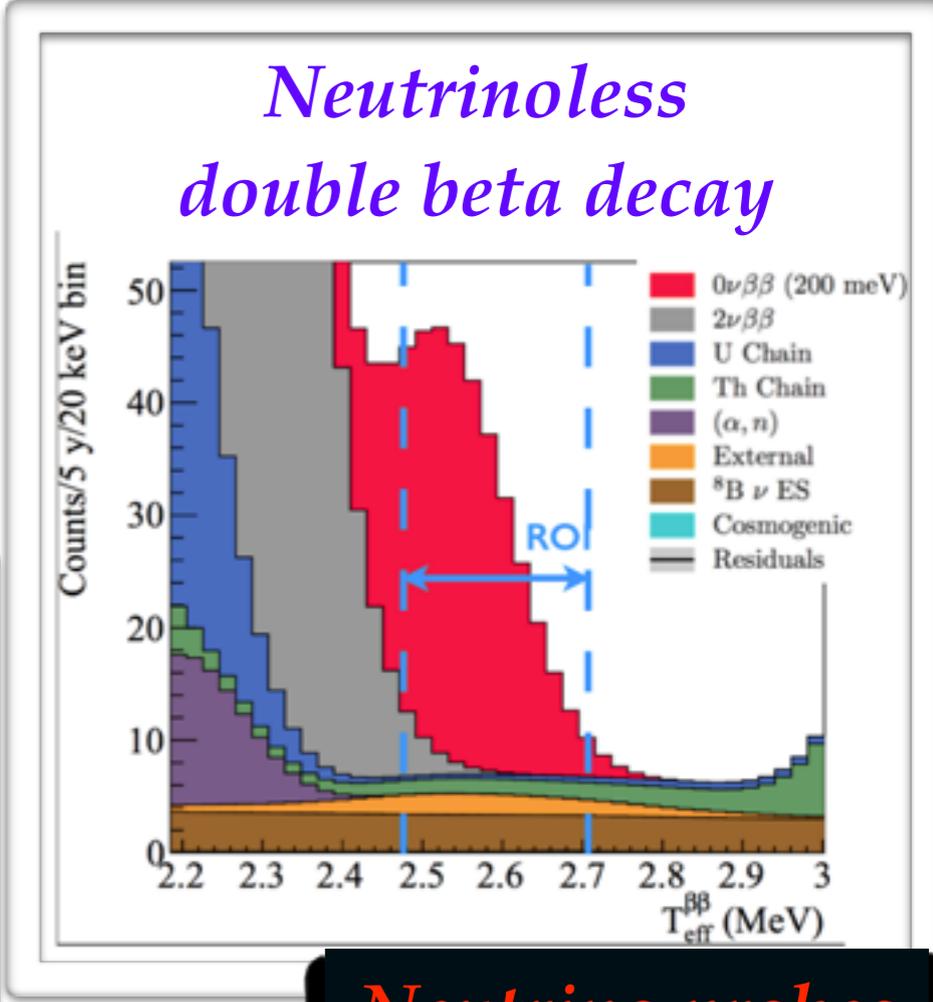
Chris Jackson — *staff scientist at PNNL*

SNO+

Multi-faceted Physics Program



- 6800ft level (5890 m.w.e.)
- 7kT H₂O buffer
- 9500 PMTs, 60% coverage
- 12m acrylic vessel
- 780T LAB



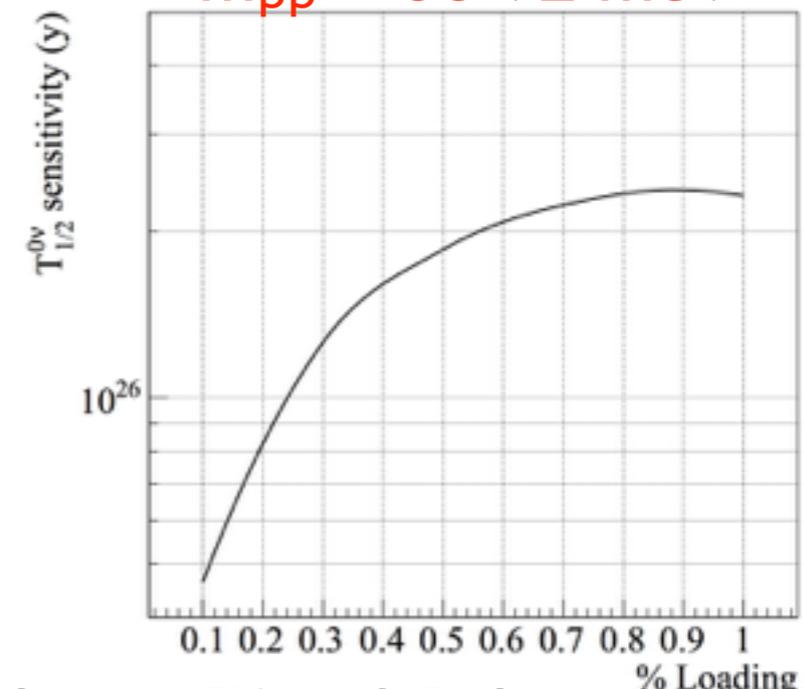
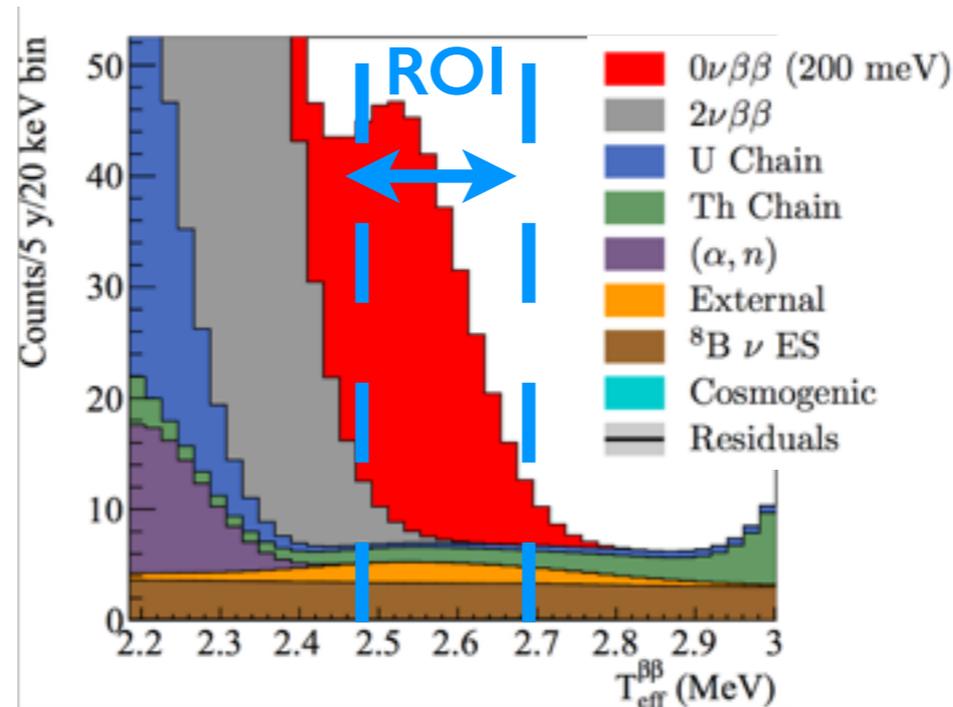
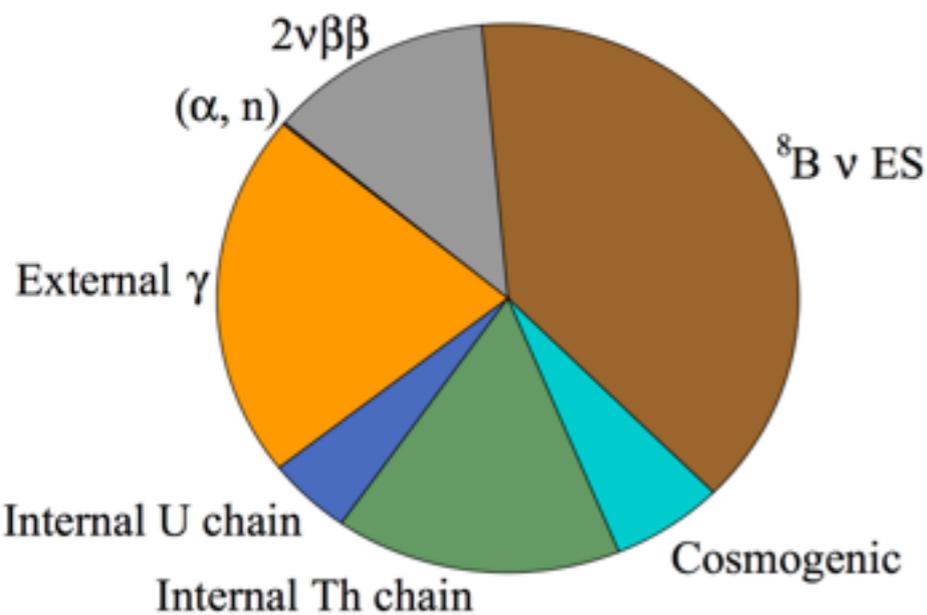
NLDBD with SNO+

- Ultra low backgrounds
 - ▶ Fiducialisation \Rightarrow self-shielding
 - ▶ Background rejection via PID and timing
 - ▶ Deep location (6000 m.w.e.)
- High detection efficiency
- Source in / out calibration
- Large target mass, easy scaling
- *Bonus: broad program includes solar, geo, reactor, supernova ν & nucleon decay*

^{130}Te :

- ❖ High natural abundance
- ❖ Favourable $2\nu\beta\beta:0\nu\beta\beta$
- ❖ R/A background rejection at 99.9% at endpoint (2.53 MeV)
- ❖ Good optical properties
 - ❖ High intrinsic γ yield
 - ❖ No abs. peaks

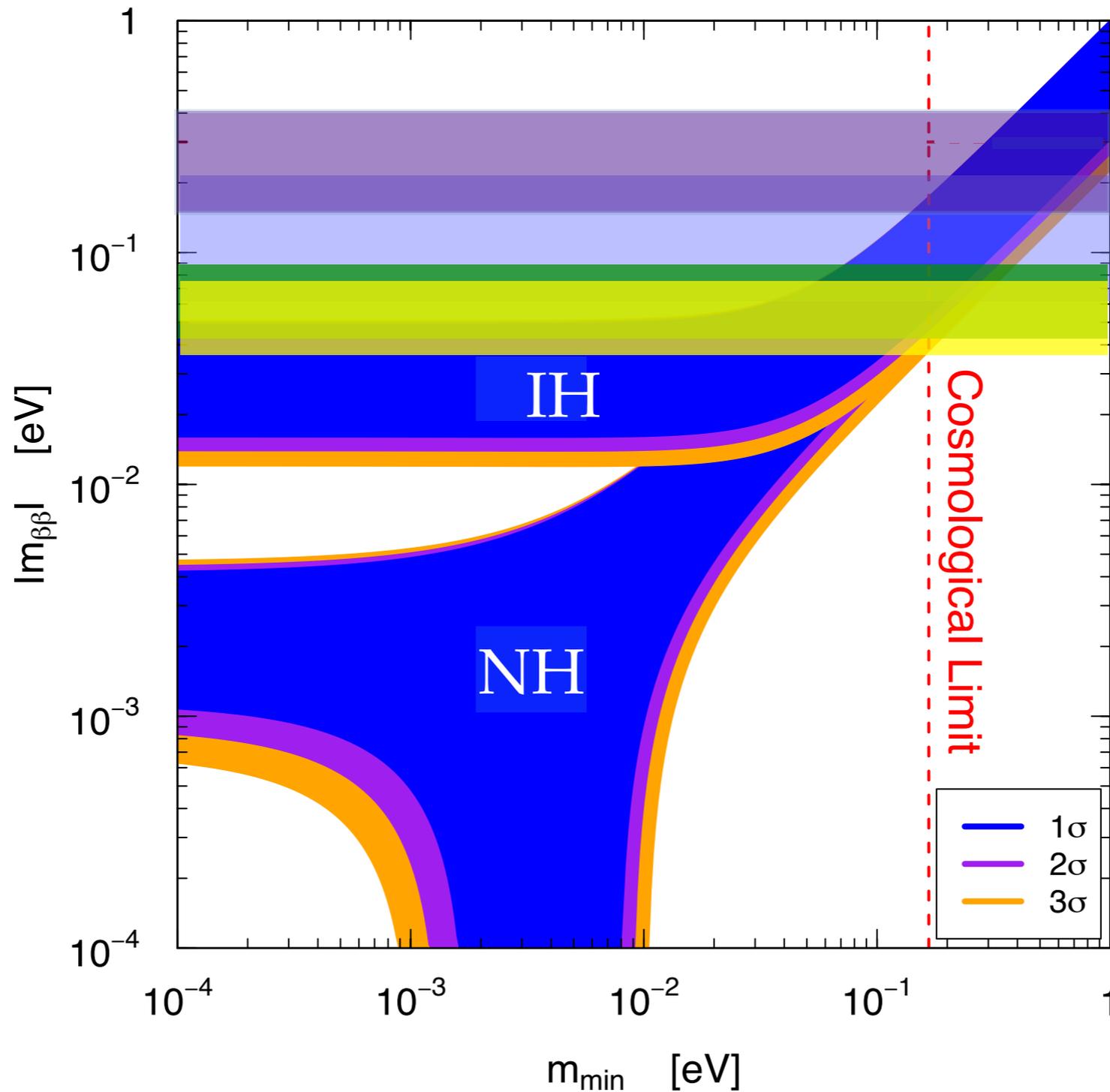
5 yrs data \Rightarrow
 $T_{1/2} > 1.96e26$ yrs 90% CL
 $m_{\beta\beta} < 38-92$ meV



Sensitivity

Current limits

KamLAND-Zen,
EXO-200,
GERDA,
CUORE-0



Future projections

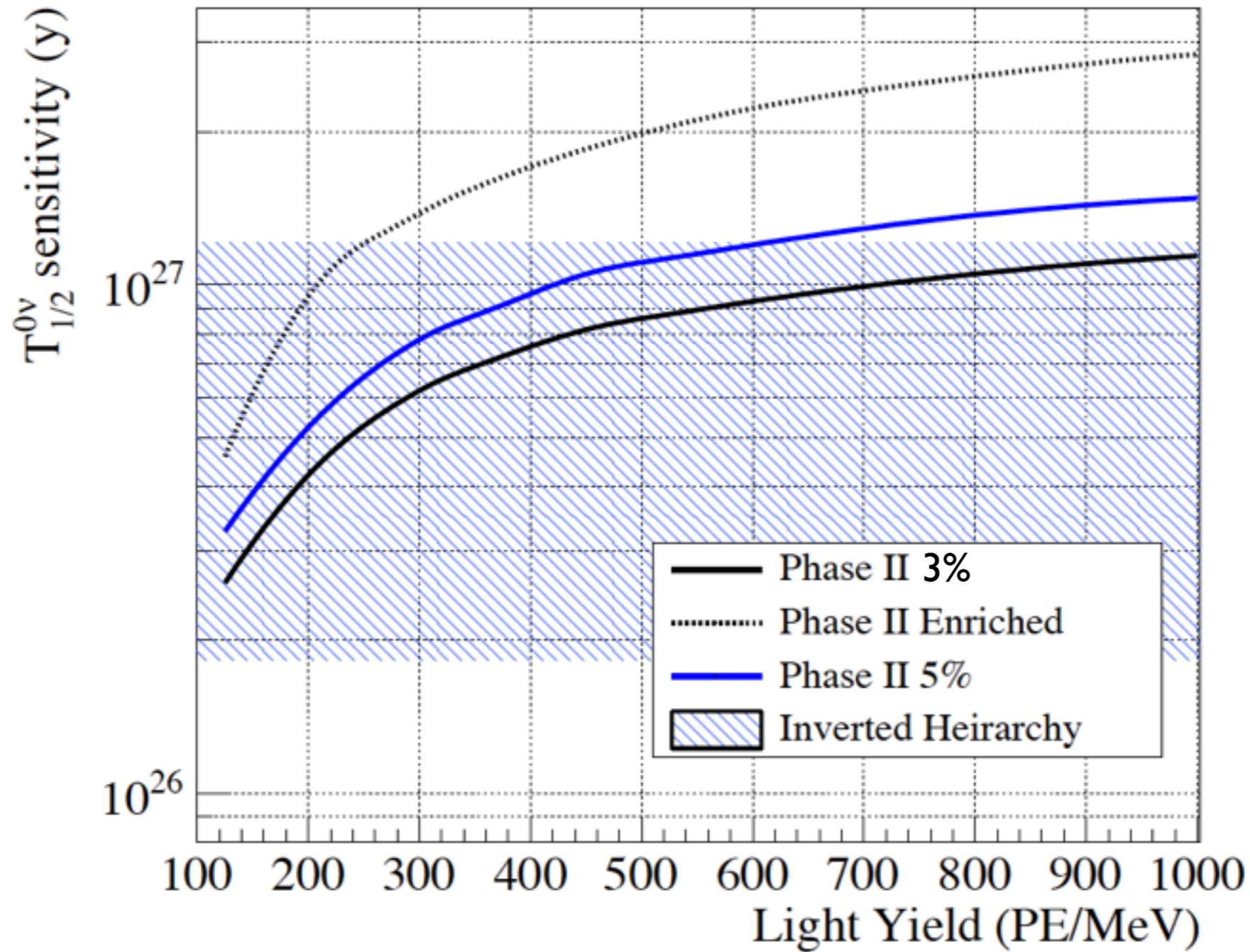
MJD projection
CUORE projection

SNO+
nat Te 0.5%

??



SNO+ Phase II

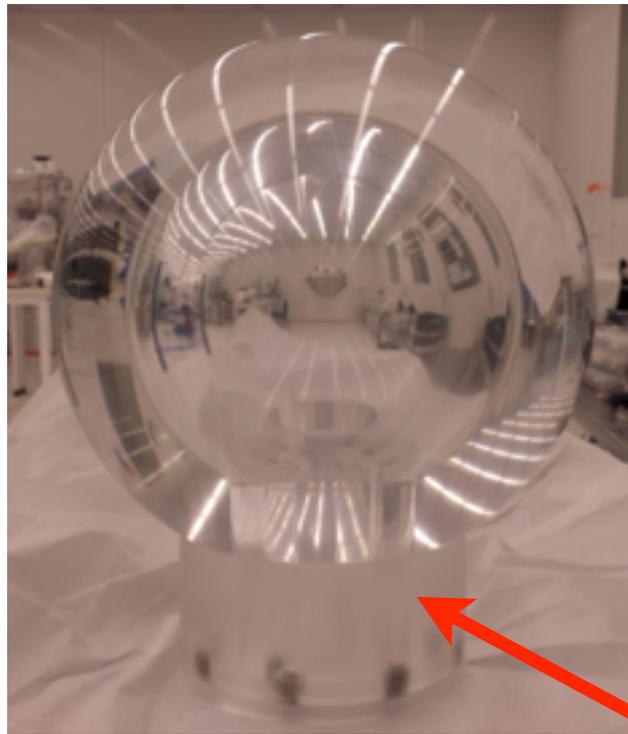
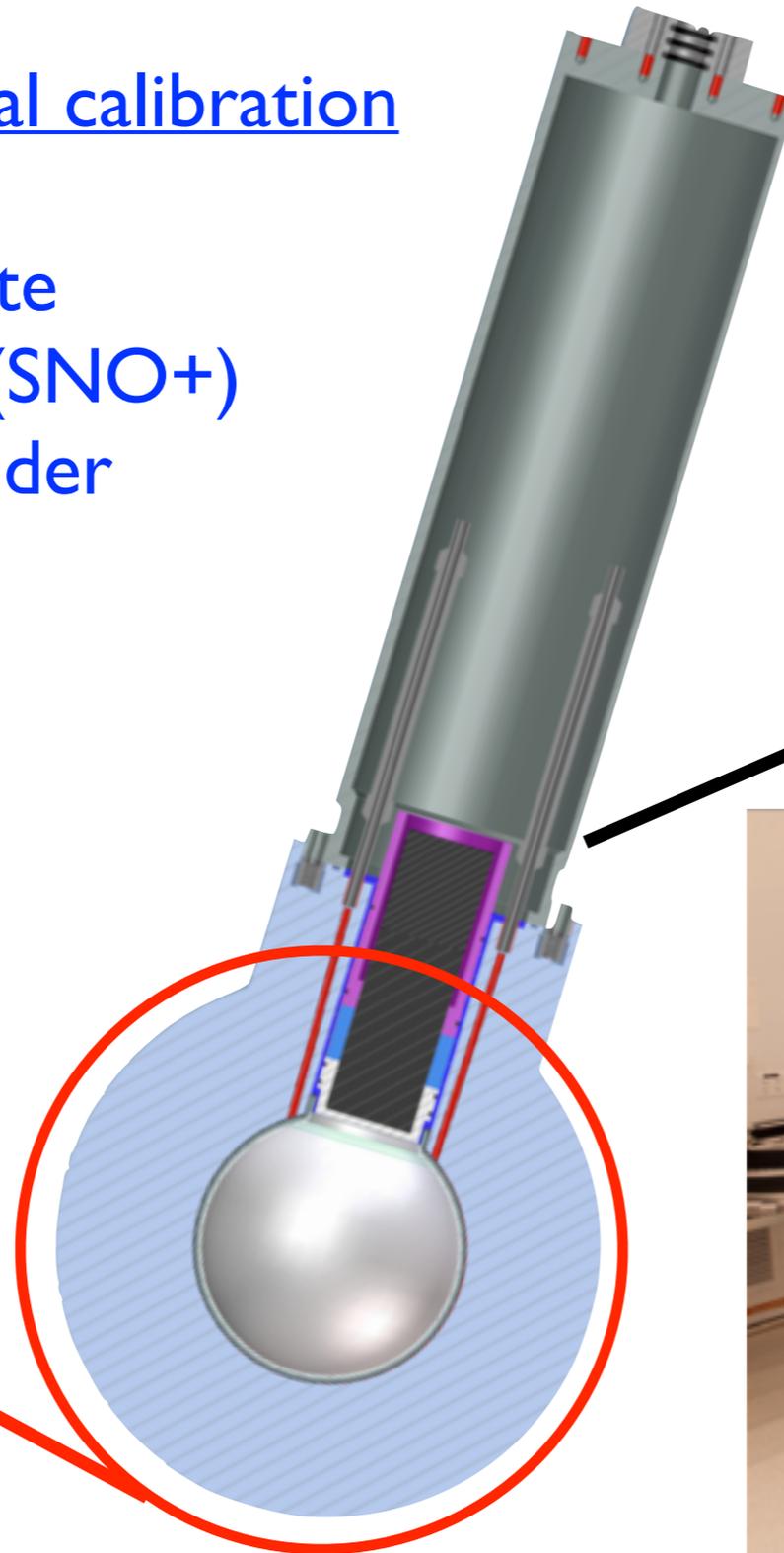
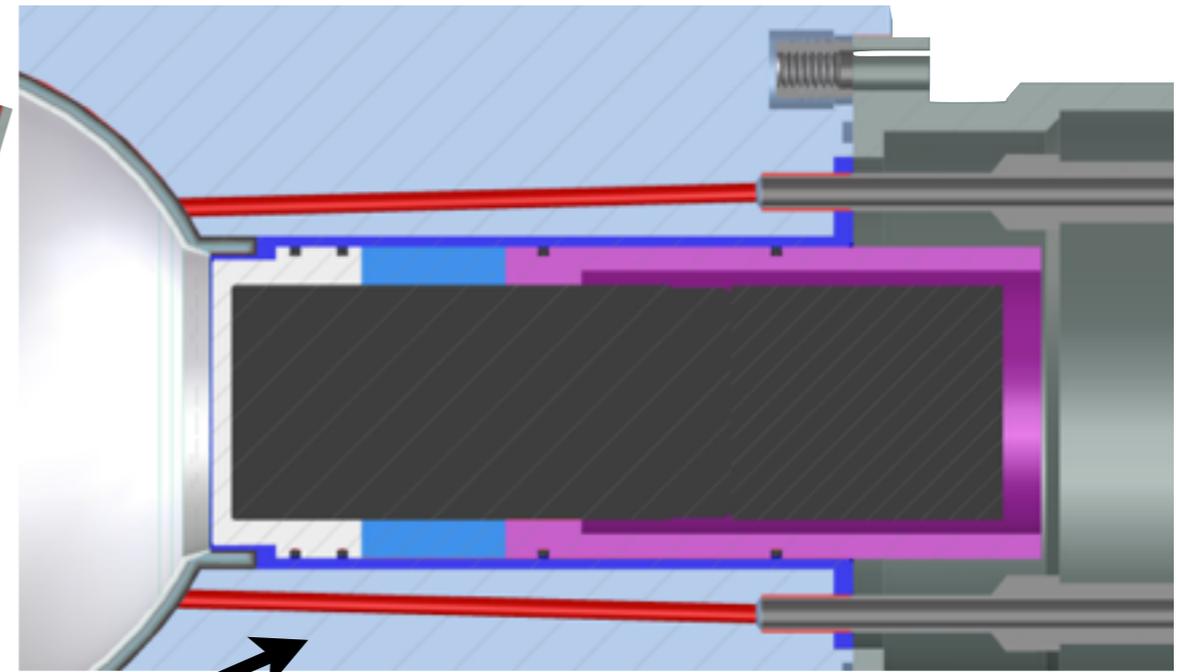


Berkeley SNO+ Projects

- Leadership Roles
 - Physics Analysis Coordinator (*Orebi Gann*)
 - Science / Executive Board (*Orebi Gann*)
 - PMT Calibrations WG lead (*Caravaca*)
 - Solar Neutrino WG lead (*Bonventre*)
 - Water-Phase Physics Analysis Coordinator (*Descamps*)
 - Detector Commissioning Manager (*Descamps*)
 - DAQ WG lead (*Descamps*)
- Simulation / Analysis
 - PMT optical model (*Jackson*)
 - Electronics & PMT calibration (*Caravaca, Descamps*)
- Detector / Hardware
 - DAQ (*Descamps, Land, Caravaca, Kéfélian*)
 - Optical calibration source (*Descamps, Land*)
 - Commissioning (*Descamps*)
- Physics Analysis
 - NLDBD sensitivity (*Jackson, Kéfélian*)
 - Solar neutrinos (*Bonventre*)
 - External backgrounds (*Prouty*)

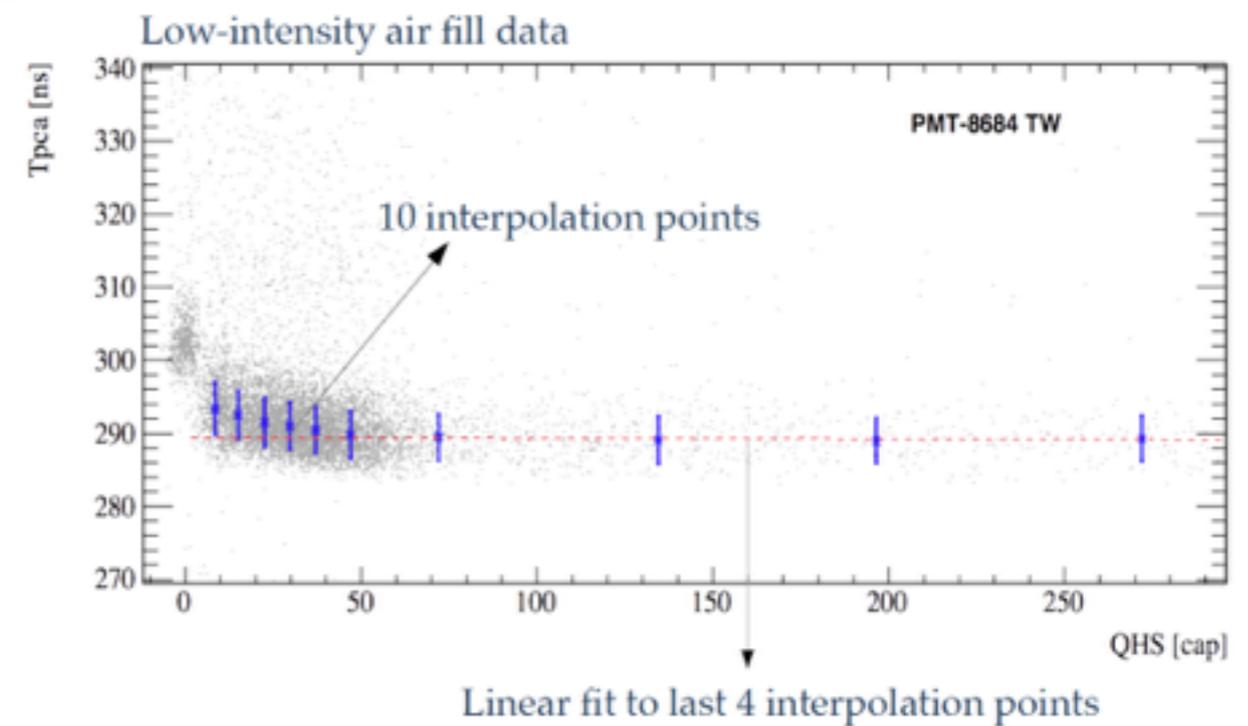
2016 Highlights

- Cherenkov optical calibration source
- Design complete
- Under review (SNO+)
- Final source under construction



2016 Highlights

- Commissioning and detector
- DAQ rewritten
- Multiple commissioning workshops
- PMT calibration complete and under review



SNO+ Control Panel

Run Control

START RESYNC STOP

Run status

Run Number: 449
Run Type:
Run Version:
Status: Stopped
Time Started:
Time Elapsed:
Run Type Word:

Expert Mode

Quick Links

OPERATOR MANUAL SHIFT REPORT

REPORT BUG

Detector control

Init crates with XLins
Init crates without XLins

Triggers ON Triggers OFF

SET HIGH THRESHOLDS

PANIC DOWN

PMT HV is OFF

Standard Runs

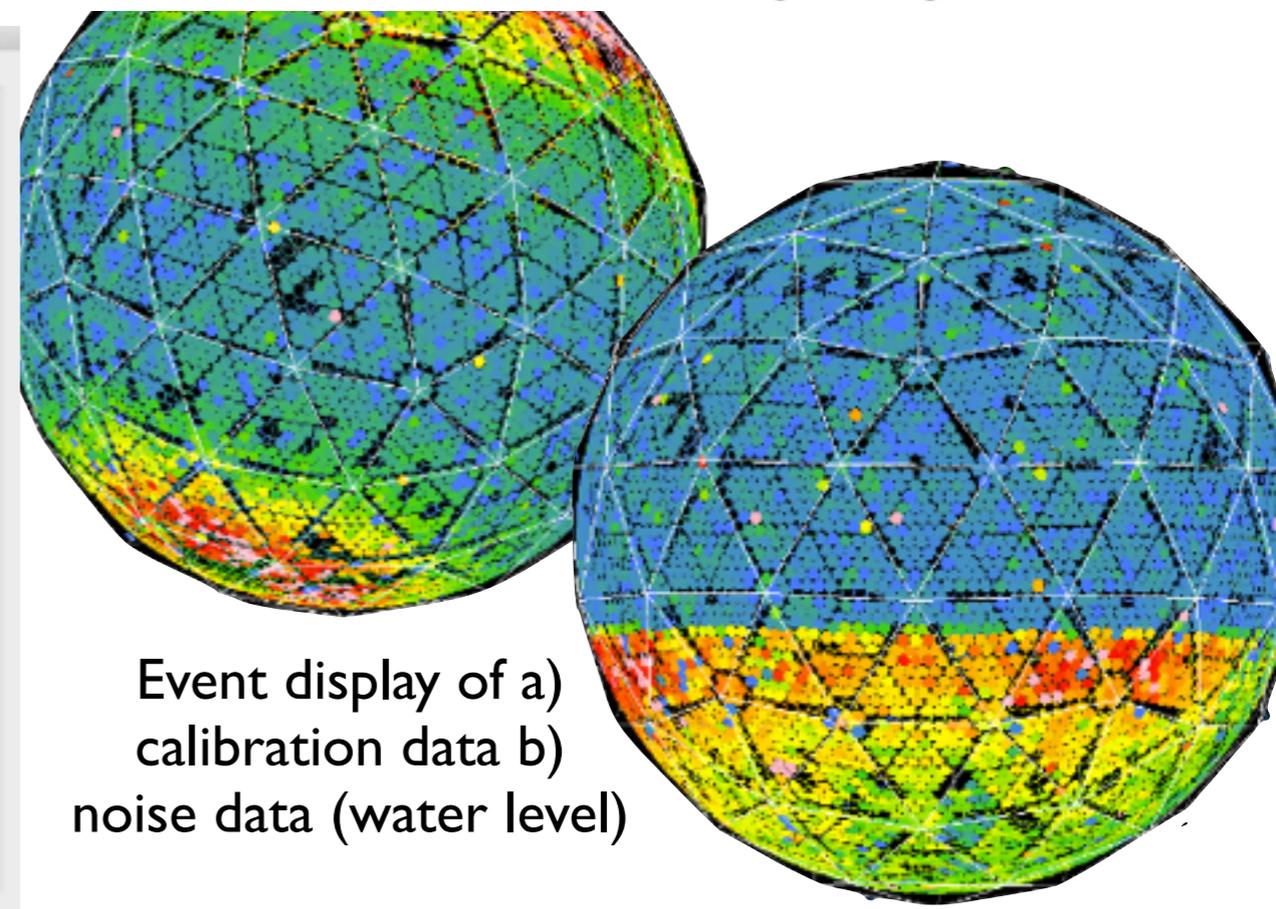
Run Name	Current value	Default values	Test Run	N-Hits
NH1100H	498.8	71.5	71.5	N-Hits
NH1100Med	115.2	257.6	257.6	N-Hits
NH1100Lo	76.5	715.5	715.5	N-Hits
NH120H	67.1	73.6	73.6	N-Hits
NH120Lo	45.5	73.6	73.6	N-Hits
OWLN	37.7	73.6	73.6	N-Hits
ESumH	2324.2	2324.2	2324.2	mV
ESumLo	2324.2	2324.2	2324.2	mV
OWLEH	2324.2	2324.2	2324.2	mV
OWLELo	2324.2	2324.2	2324.2	mV
Prescale	100.0	100.0	100.0	Hz
PulseGT	0.0	10.0	10.0	Hz

ECA SMELLIE TELLIE

Start ECA Standard Run

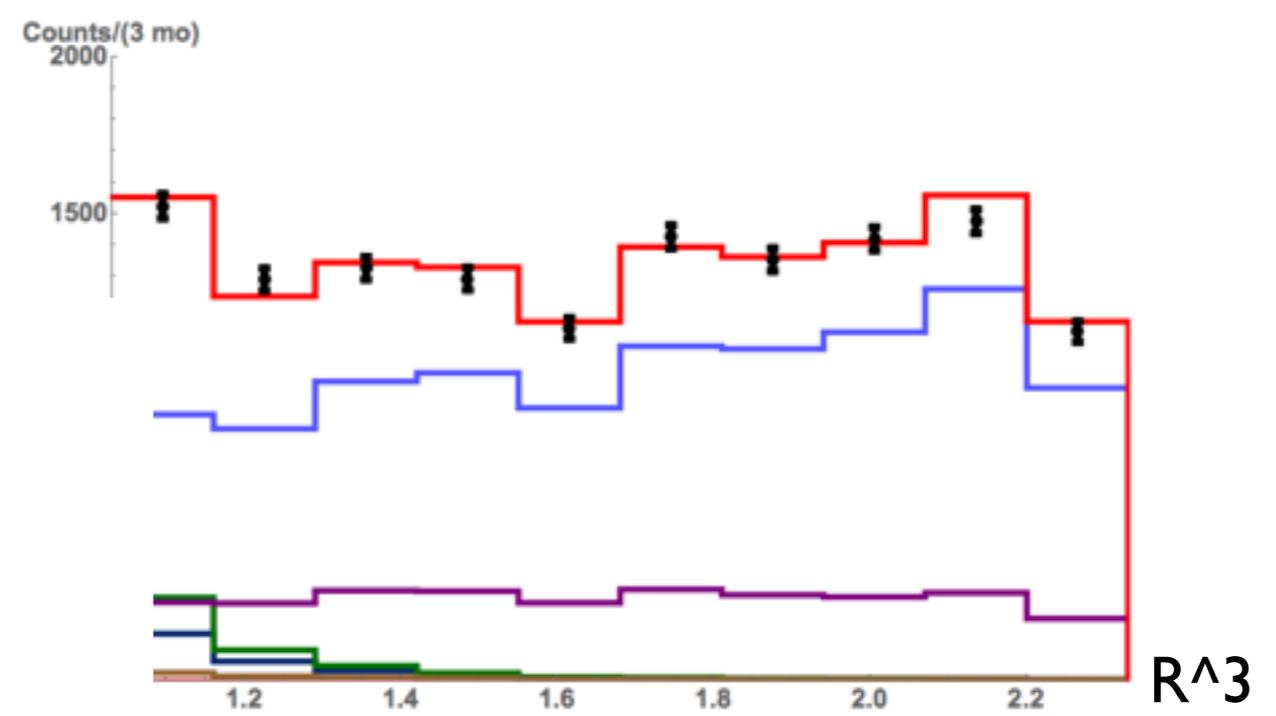
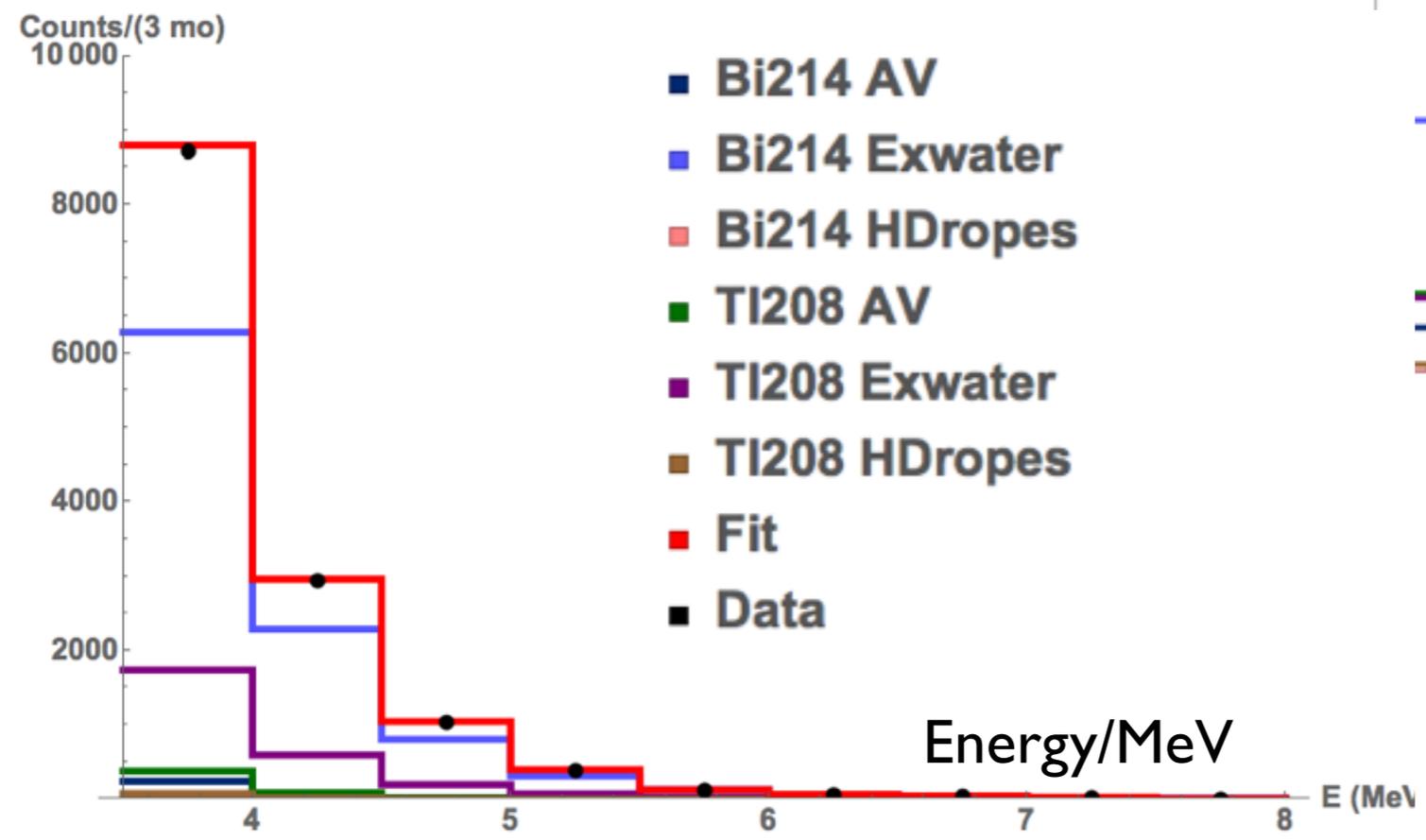
Pattern: SNO style
Calibration type: POST
Number of TSlope Points: 50
Number of events: 200
Pulsar rate for ECA: 100 Hz

Start Single ECA Run

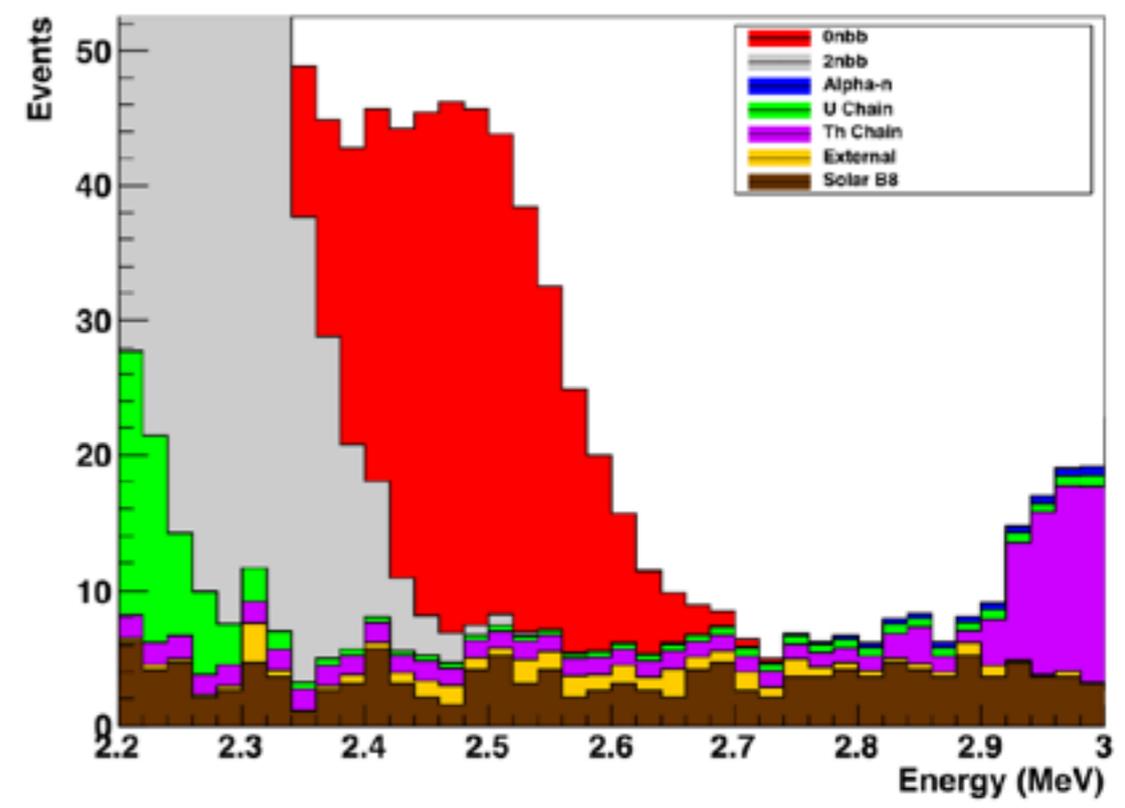


2016 Highlights

- Physics Analysis
 - Water-phase external backgrounds
 - NLDBD sensitivity studies



- Externals: 2nd dominant background
- Best measured in water data
- ⇒ constraint for DBD measurement

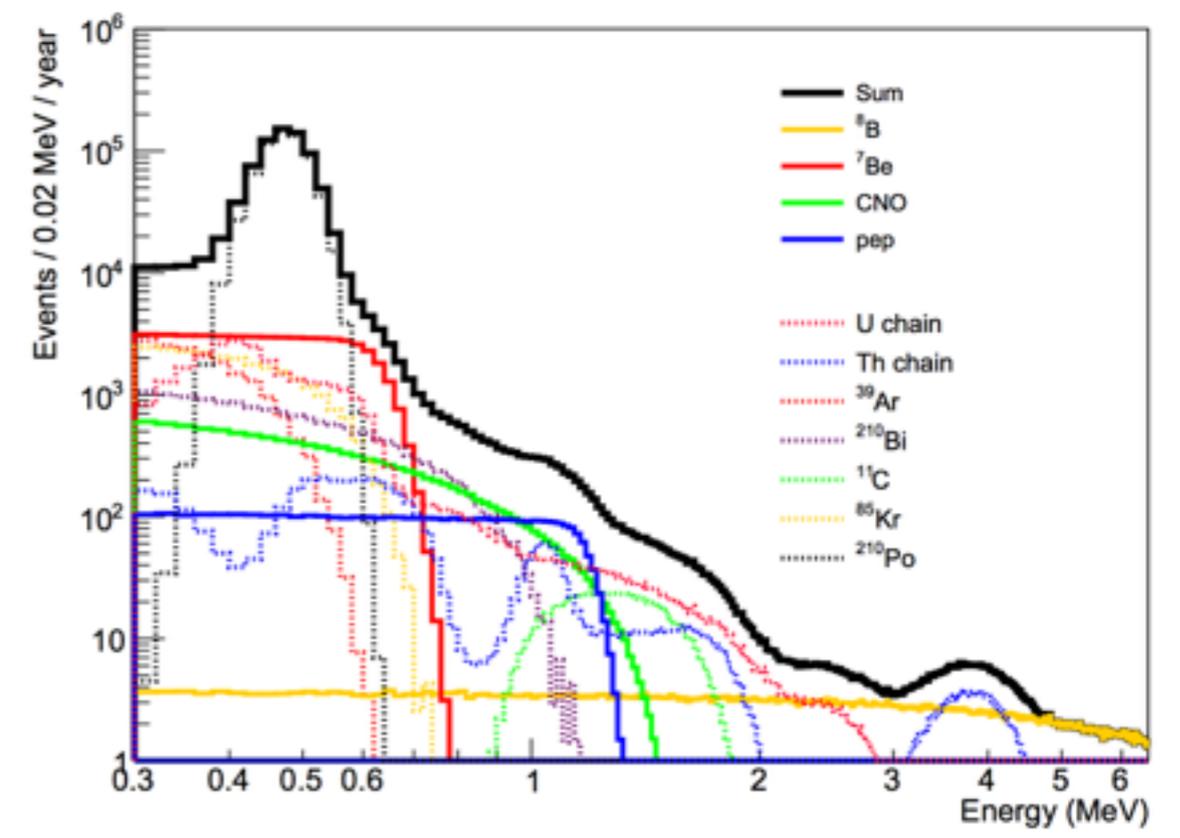
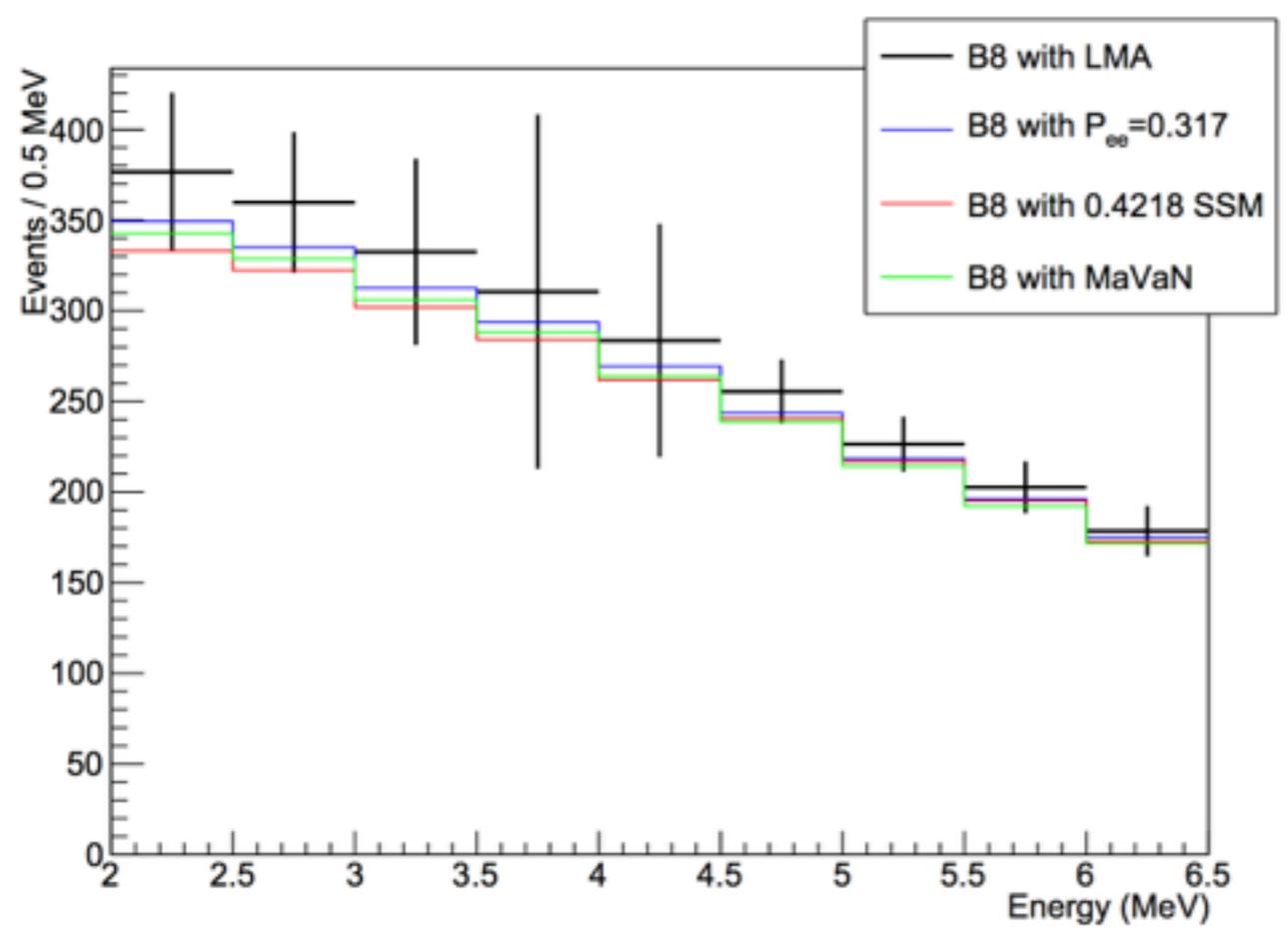
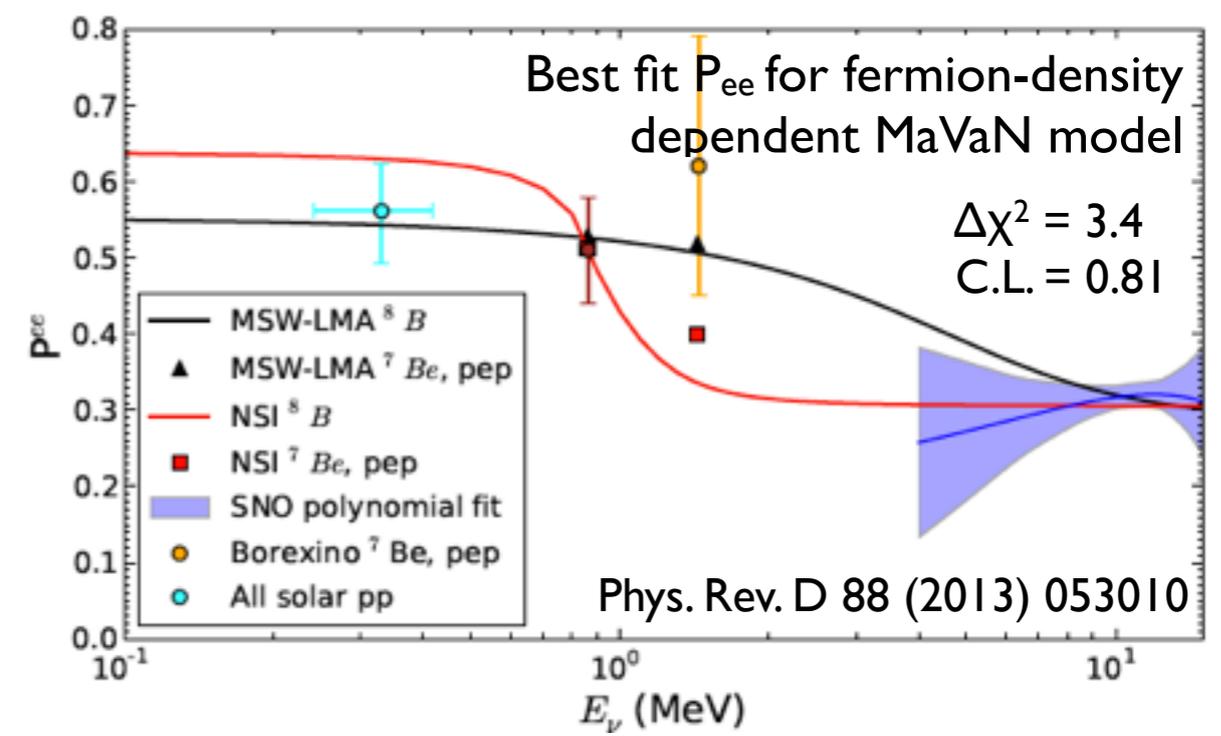


2016 Highlights

- Physics Analysis
 - Solar neutrino studies

Exciting questions still to address:

- o Probe neutrino interaction with matter;
- o Resolve solar metallically uncertainty



2017 Deliverables

LBNL group deliverables:

Detector Status

- Stable, robust DAQ software
- Full electronics calib. analysis
- Full PMT calibration analysis
- Detector channel status
- Concentrator aging model

Cherenkov Source

- Complete final source
- Commission, test & deploy
- QC / QA

Detector Commissioning

Analysis

- Analysis plan / coordination
- Blindness criteria
- External backgrounds analysis
- Analysis review
- Physics results (nucleon decay)
- Publication!

SNO+ Schedule:

- Complete water fill: Nov '16
- Nucleon decay physics data: Jan '17
- Scintillator fill: summer 2017
- Te loading: 2018

Berkeley SNO Projects

- Leadership Roles

- **Physics Analysis Coordinator** (*Orebi Gann*)

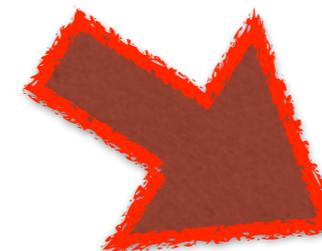
- Spearheading multiple new analyses across the collaboration

- *Search for solar hep neutrinos: final unmeasured solar nu flux*
 - *Search for diffuse SN nu background*
 - *Search for Lorentz Violating effects in solar neutrino flux*
 - *Measurement of $\sin^2\theta_W$*
 - *Search for dinucleon decay modes*
 - *Neutrino lifetime*
 - *Atmospheric neutrinos*
 - *Cosmogenic neutrons*

- **Atmospheric Neutrino WG lead** (*Caravaca*)

- Physics Analysis

- *Neutrino lifetime* (*Land*)
 - *Atmospheric neutrinos* (*Caravaca, Prouty, Singh*)
 - *Cosmogenic neutrons* (*Kéfélian*)



Over half a dozen physics publications expected in the next 1–2 years

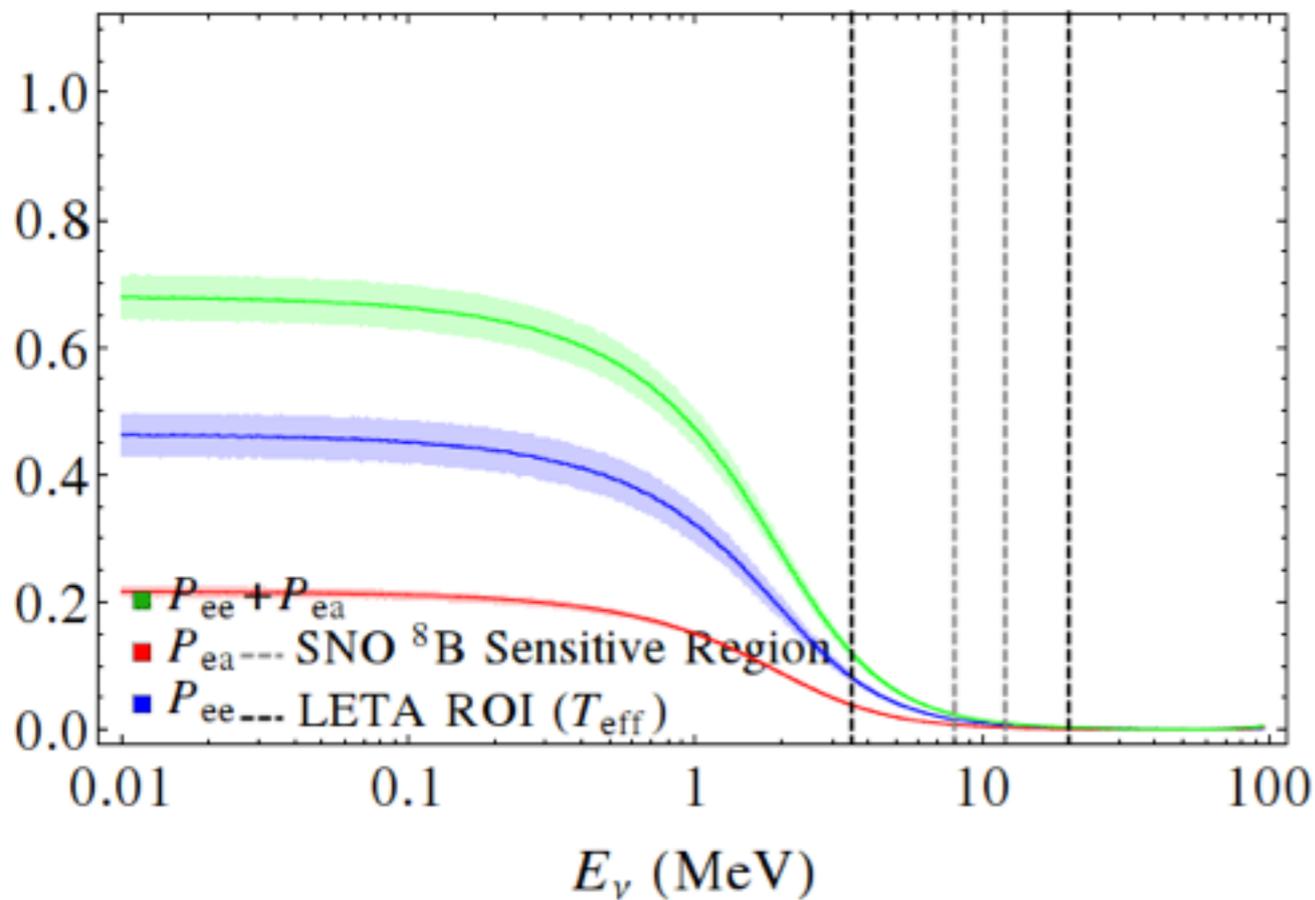
Berkeley SNO Projects

- Neutrino lifetime (*Land*)

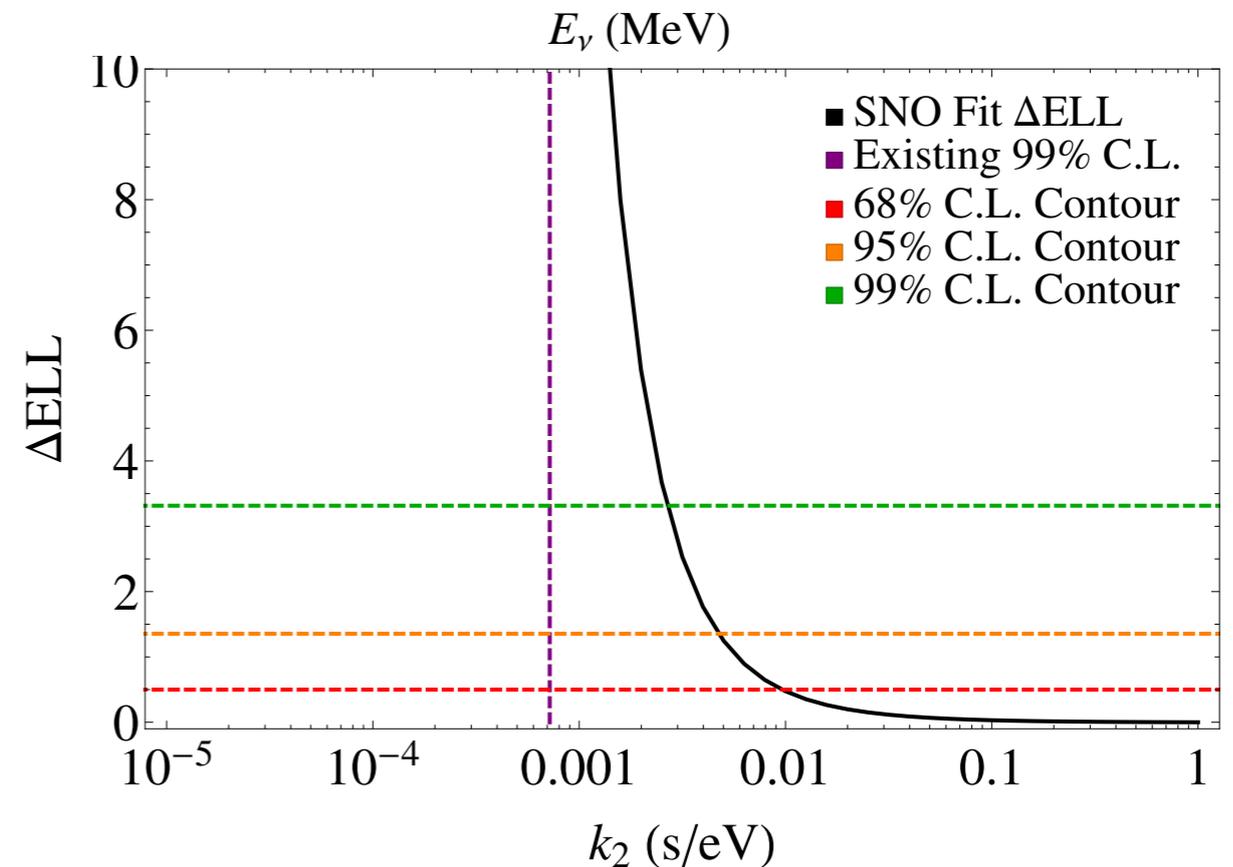
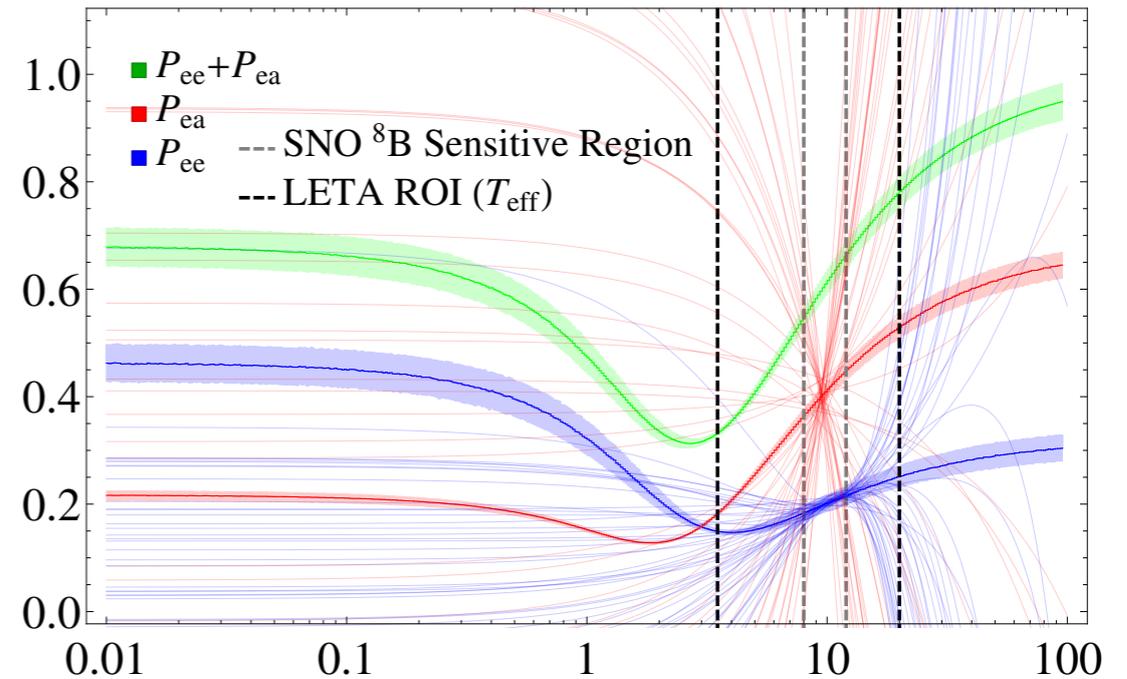
Extract lifetime limit from shape of ν_e energy spectrum

Decay parameter $k = \text{lifetime} / \nu$ mass

$k_2 = 1.00e-6 \text{ (s/eV)}$



$k_2 = 0.0001$



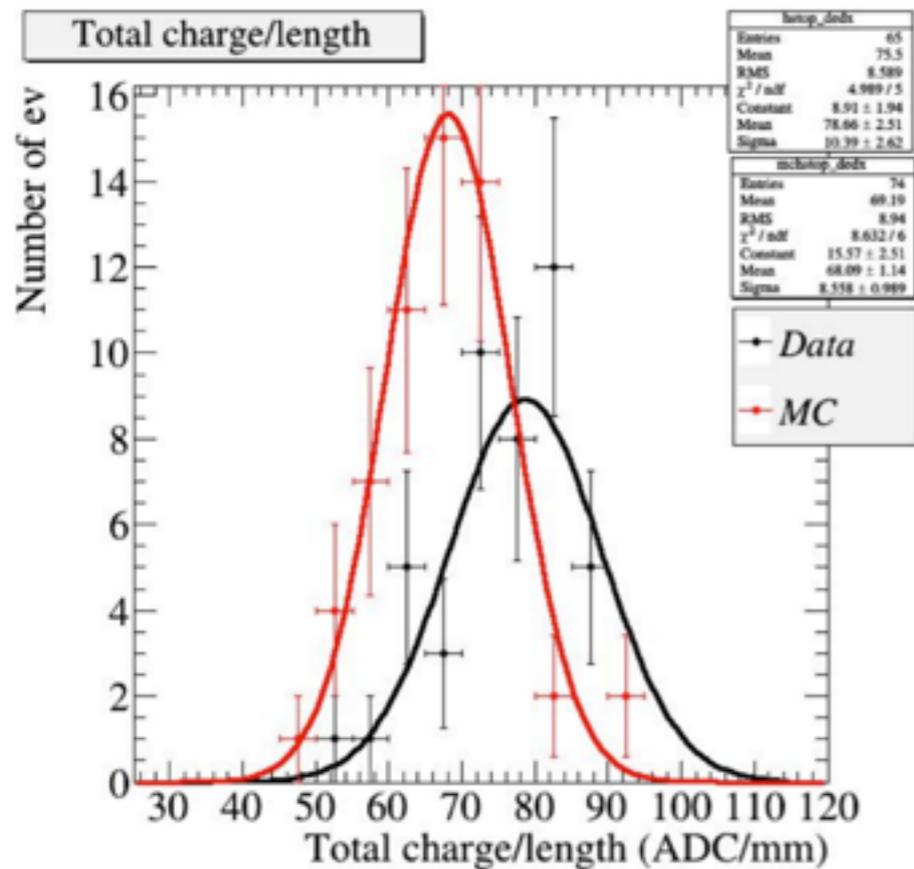
Berkeley SNO Projects

- Atmospheric neutrinos (*Caravaca, Prouty, Singh*)

Neutron production (ν energy & flavour)

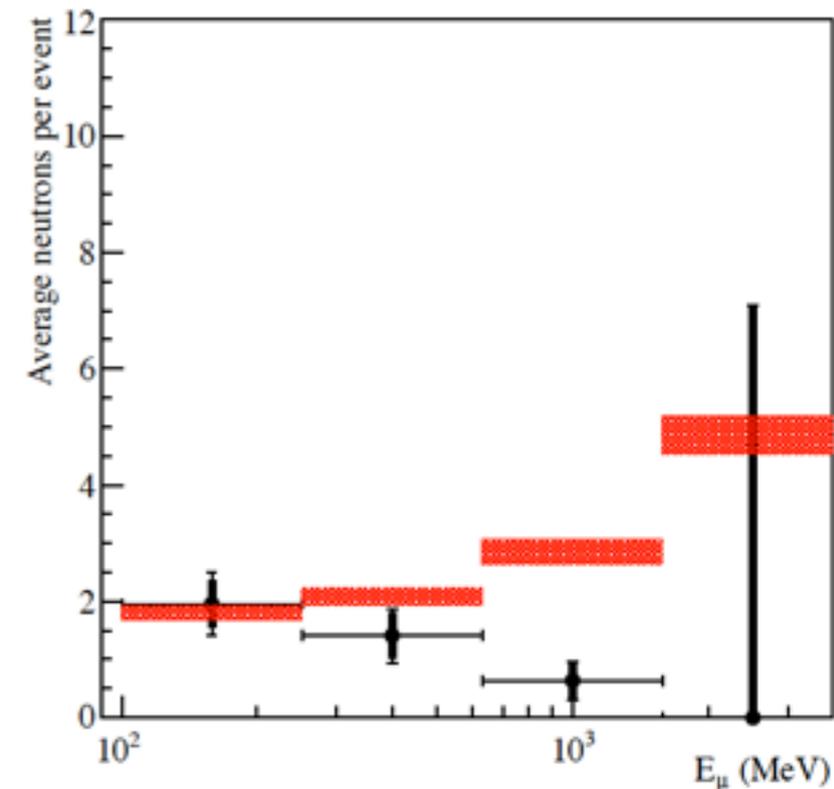
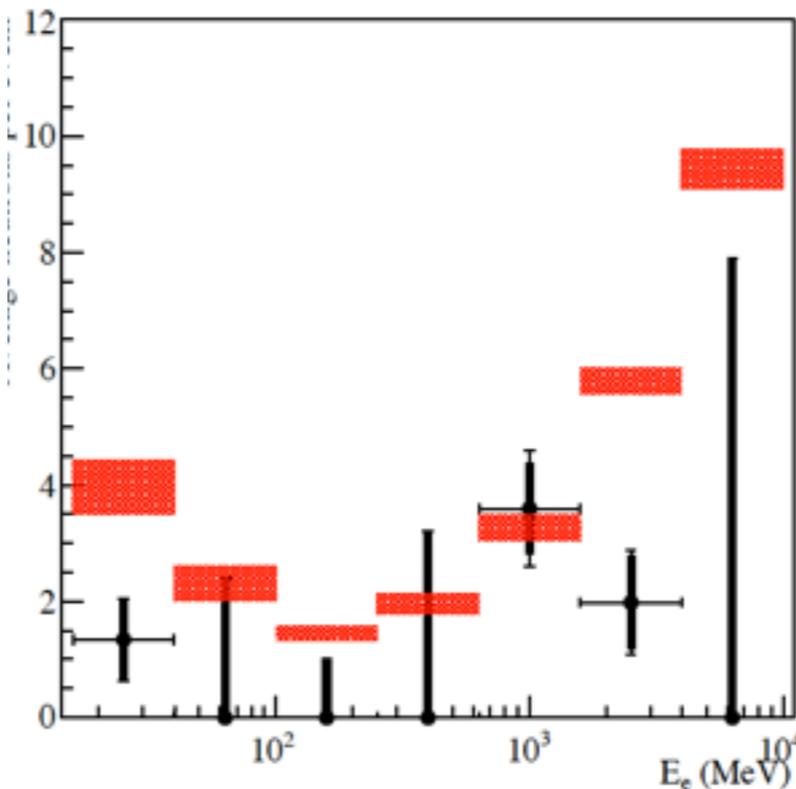
Understand details of ν interactions

Particle/anti-particle separation (charge identification) \Rightarrow cross sections



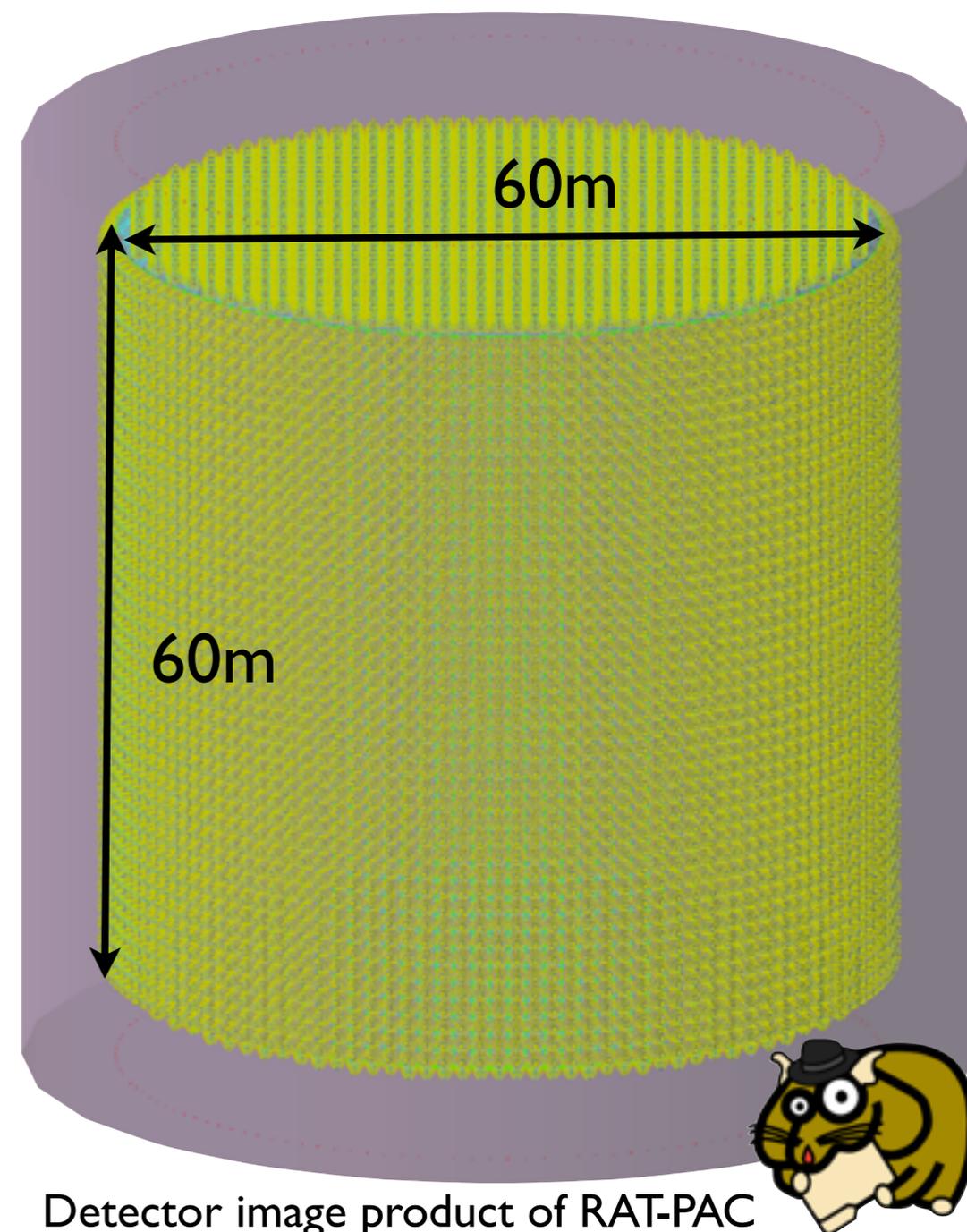
Data / MC comparison for stopping muons (high E calibration)

Neutron multiplicity for single e-like and μ -like events (E_i)



THEIA

- Large-scale detector (50-100 kton)
 - Water-based scintillator target
 - Fast, high-efficiency photon detection with high coverage
 - Deep underground (Homestake)
 - Isotope loading (Gd, Te, Li...)
 - *Flexible!* Target, loading, configuration
- ➡ **Broad physics program!**



Detector image product of RAT-PAC

Concept paper - [arXiv:1409.5864](https://arxiv.org/abs/1409.5864)

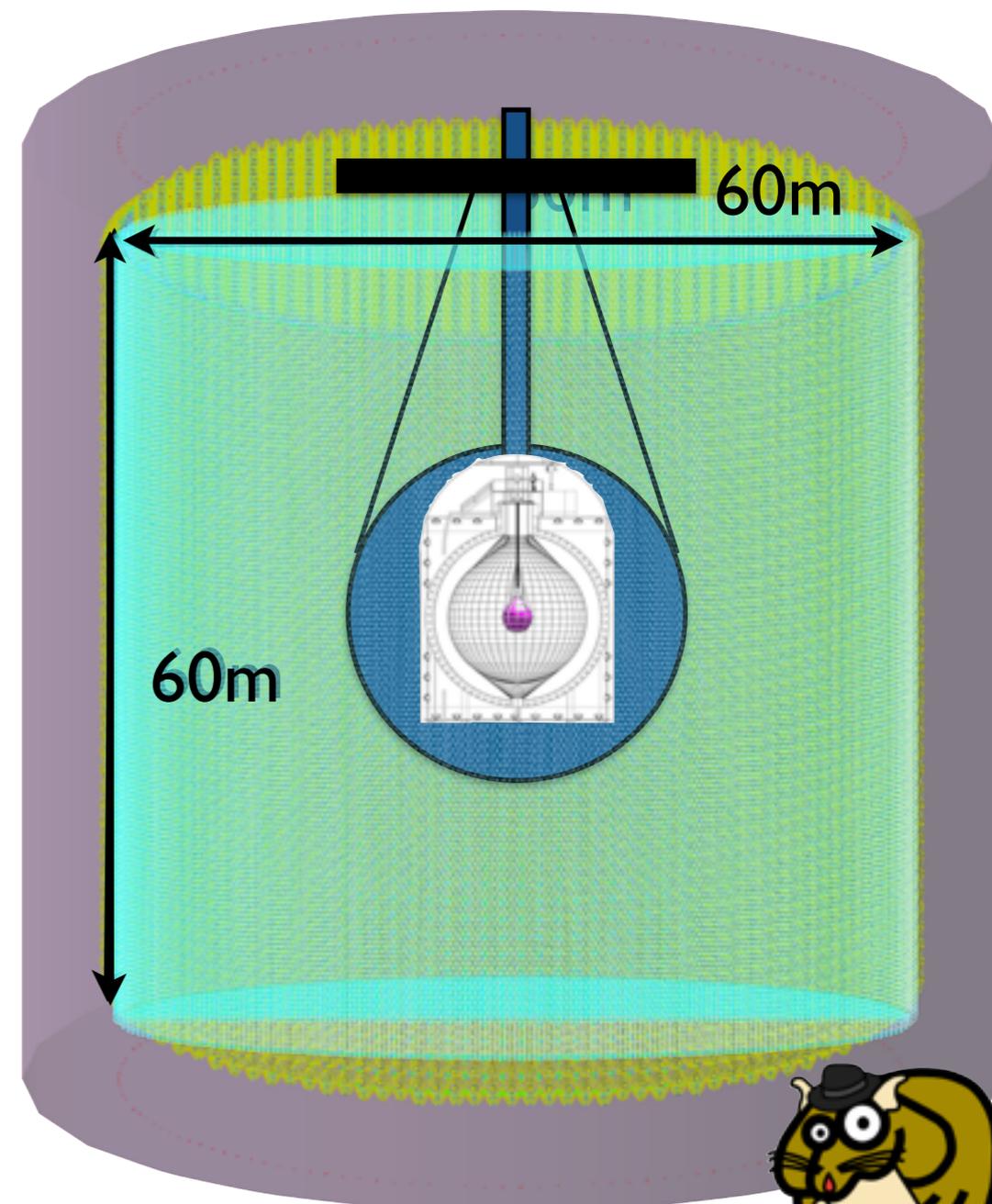
THEIA

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- Deep underground (Homestake)
- Isotope loading (Gd, Te, Li...)
- *Flexible!* Target, loading, configuration

➡ **Broad physics program!**

Keystone: Cherenkov/scintillation separation
Supported by LBNL LDRD (FY '15-16)

Concept paper - [arXiv:1409.5864](https://arxiv.org/abs/1409.5864)



Detector image product of RAT-PAC

THEIA Physics Program

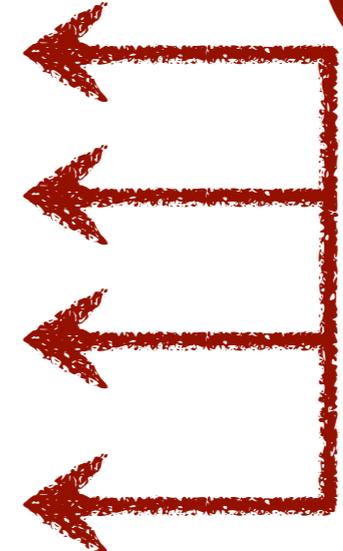


1. Neutrinoless double beta decay
2. Solar neutrinos (solar metallicity, luminosity)
3. Geo-neutrinos
4. Supernova burst neutrinos & DSNB
5. Source-based sterile searches

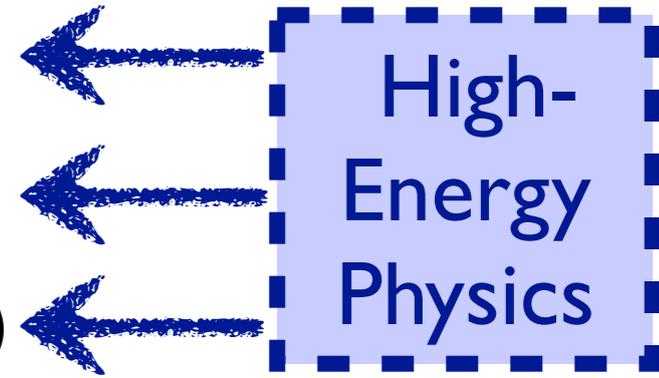


6. Nucleon decay
7. Long-baseline physics (mass hierarchy, CP violation)

Physics over 5 orders of magnitude



Nuclear Physics



High-Energy Physics

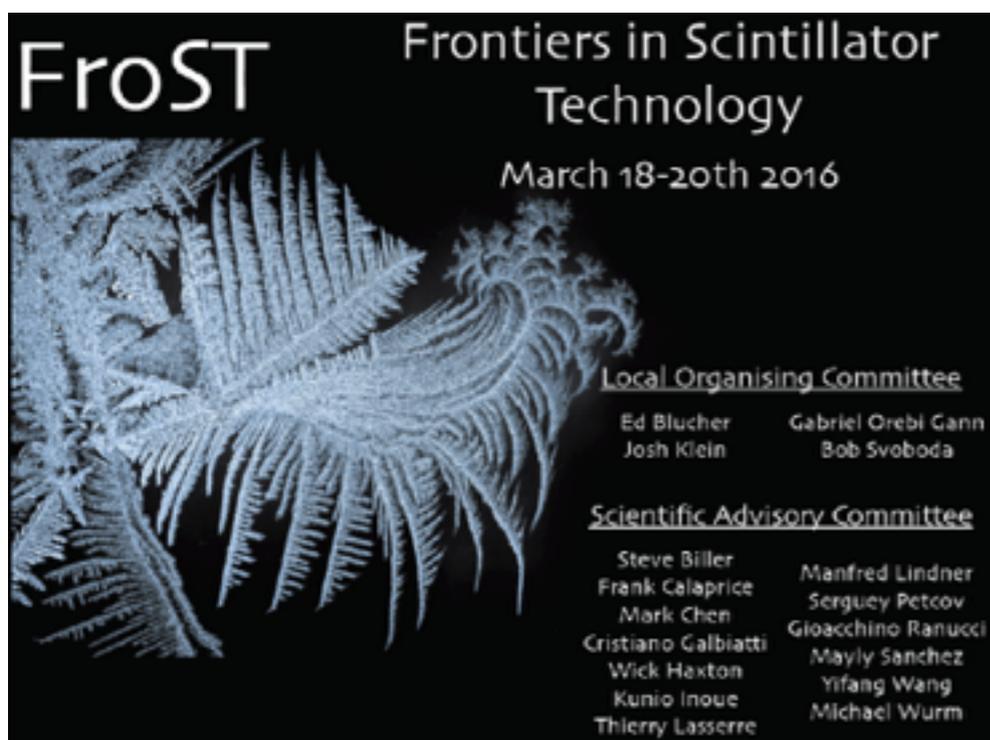
Remarkably, the same detector could show that neutrinos and antineutrinos are the same, *and* that “neutrinos” and “antineutrinos” oscillate differently

Leptogenesis

THEIA at LBNL

Responsibilities:

1. Head of international THEIA Interest Group (Orebi Gann)
2. Head of software development group (Caravaca)
3. Sensitivity studies for different cocktails (Bonventre, Madigan)
4. Demonstration of Cherenkov/scintillation separation (fast timing and ring imaging) (Land, Caravaca) *[supported by LBNL LDRD]*



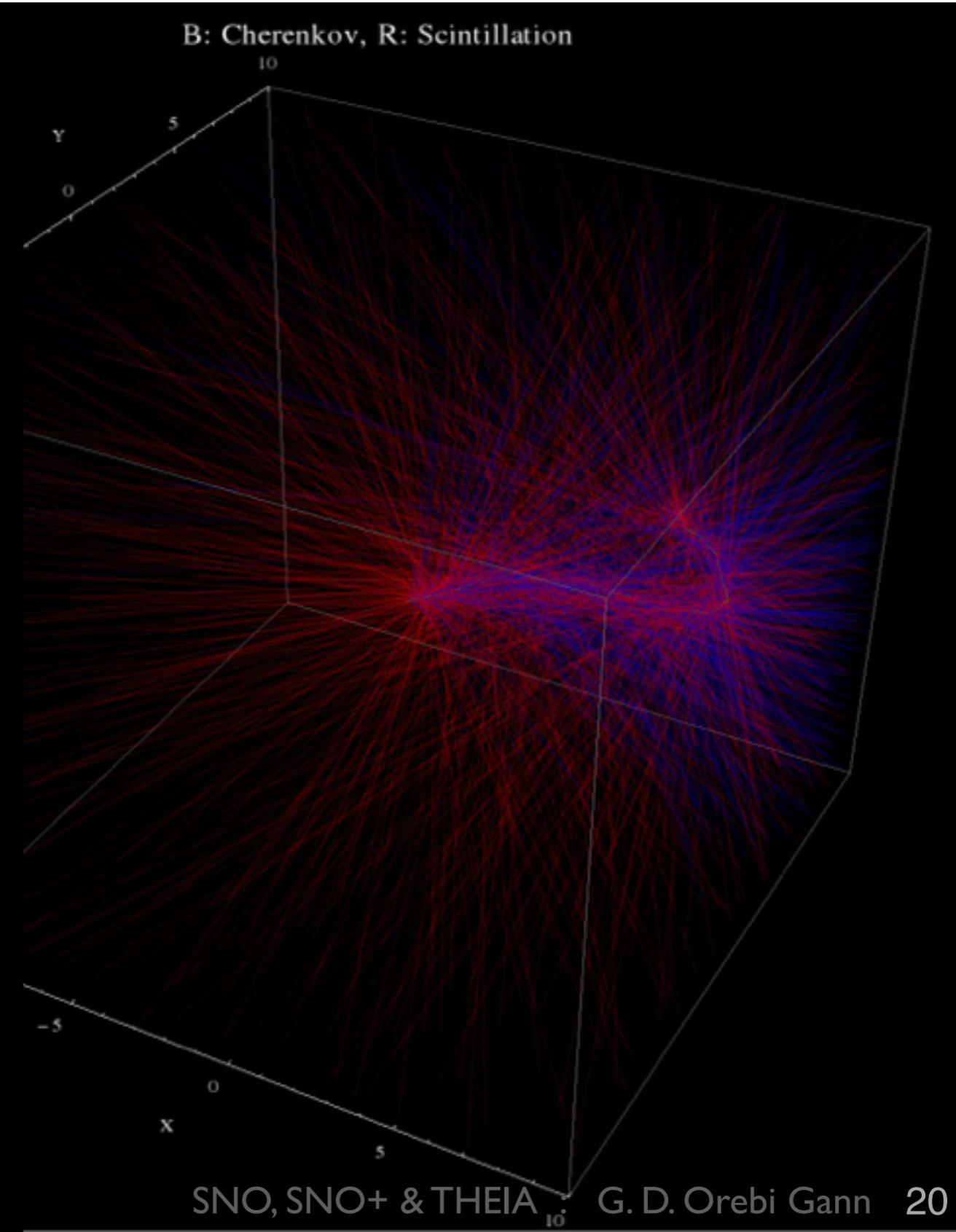
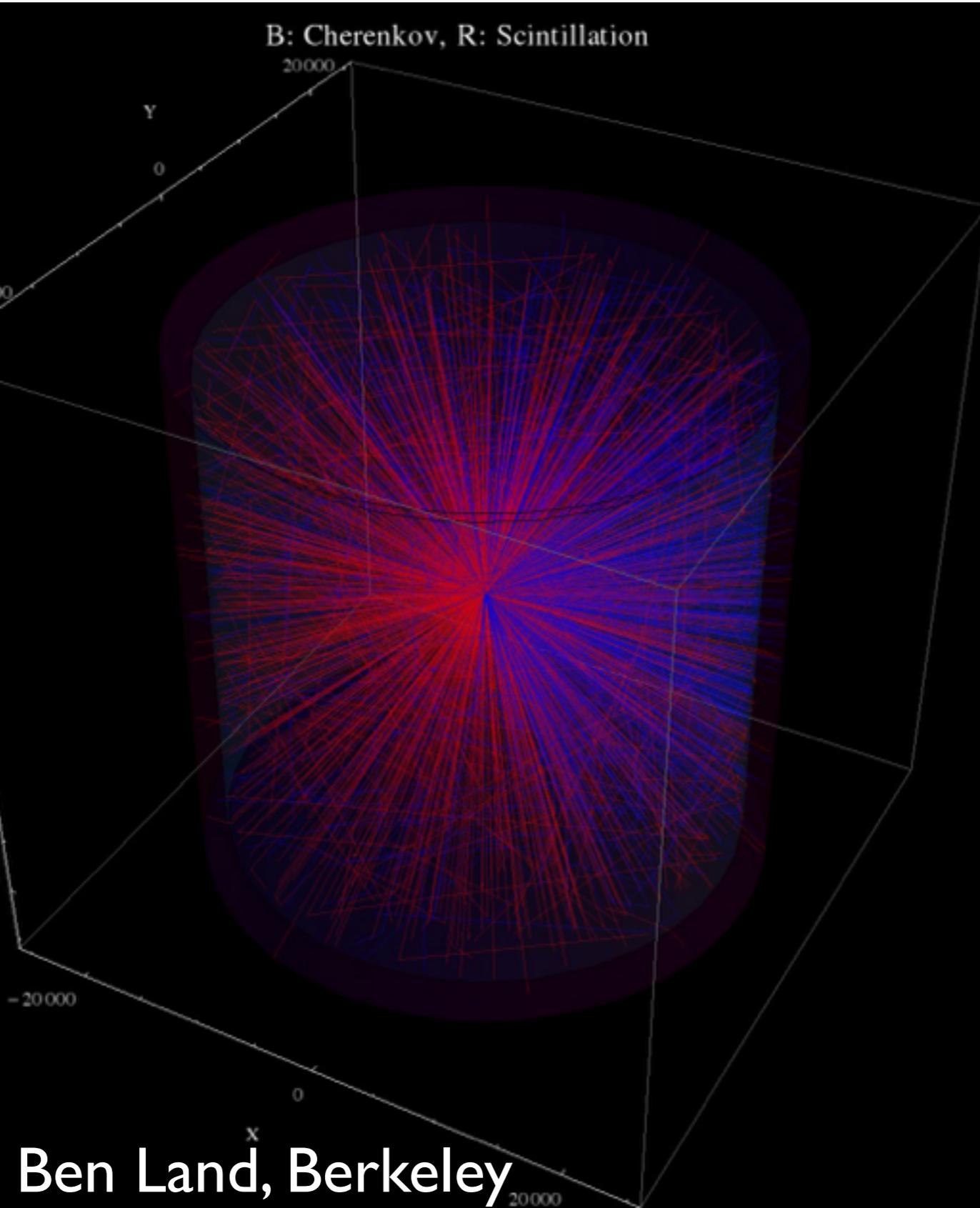
International workshop at FNAL (Mar '16)
 Proto-collaboration meeting, Mainz (Oct '16)



FroST - Topical Workshop for THEIA

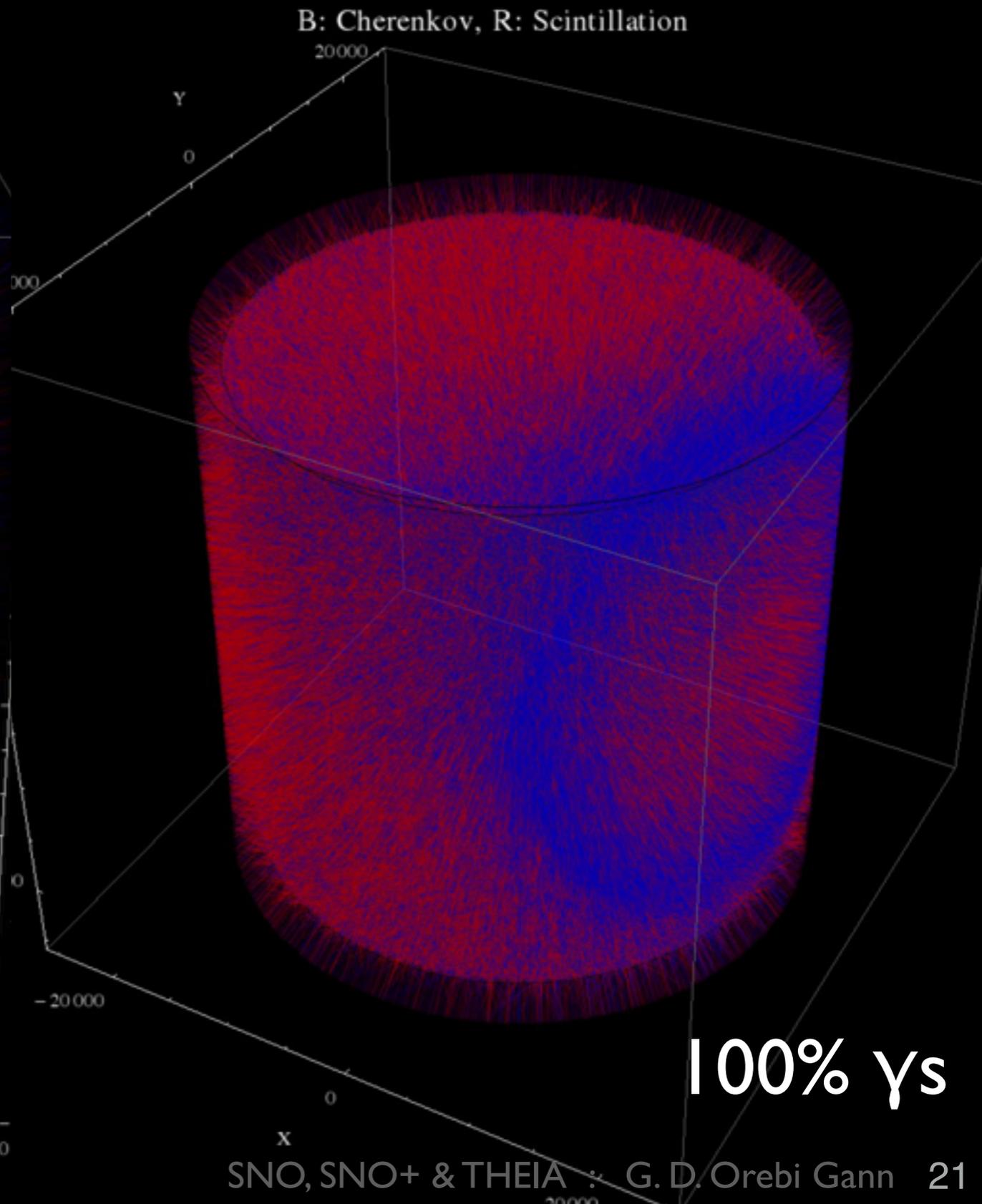
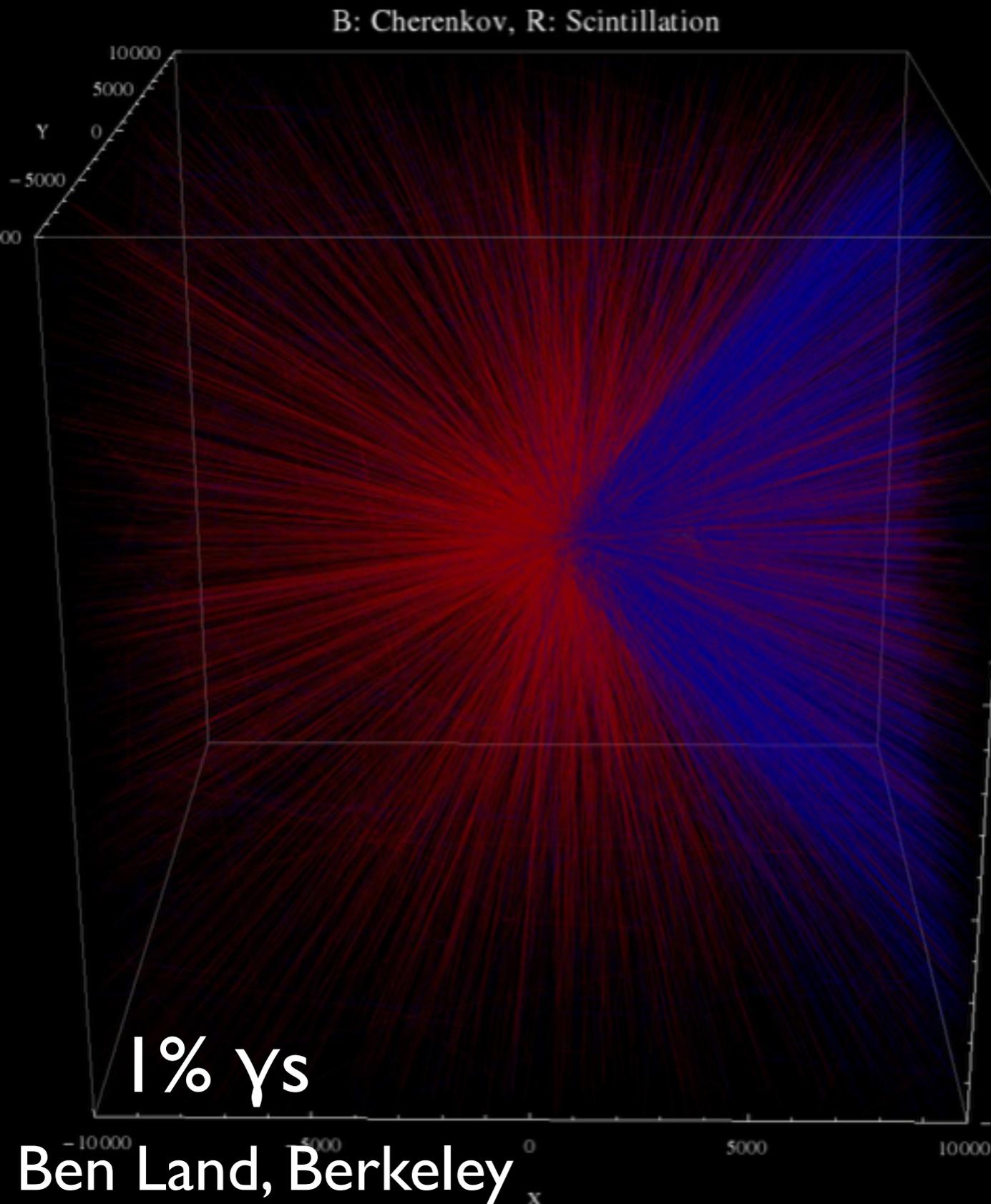
Signal separation

3 MeV β , 5% WbLS, 50kt, 90%



Ring Imaging

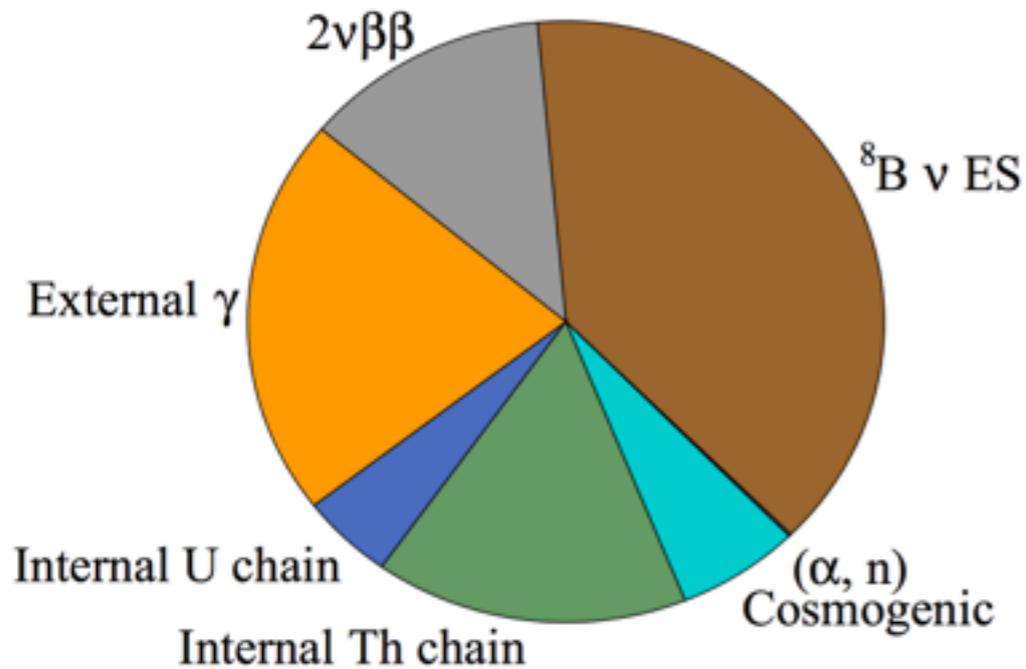
1 GeV β , 5% WbLS, 50kt, 90%



THEIA NLDBD Sensitivity

Phys.Rev.Lett. 110 : 062502 (2013);
 SNO+ white paper (in progress);
 Phys. Rev. D 87 no. 7 : 071301 (2013)

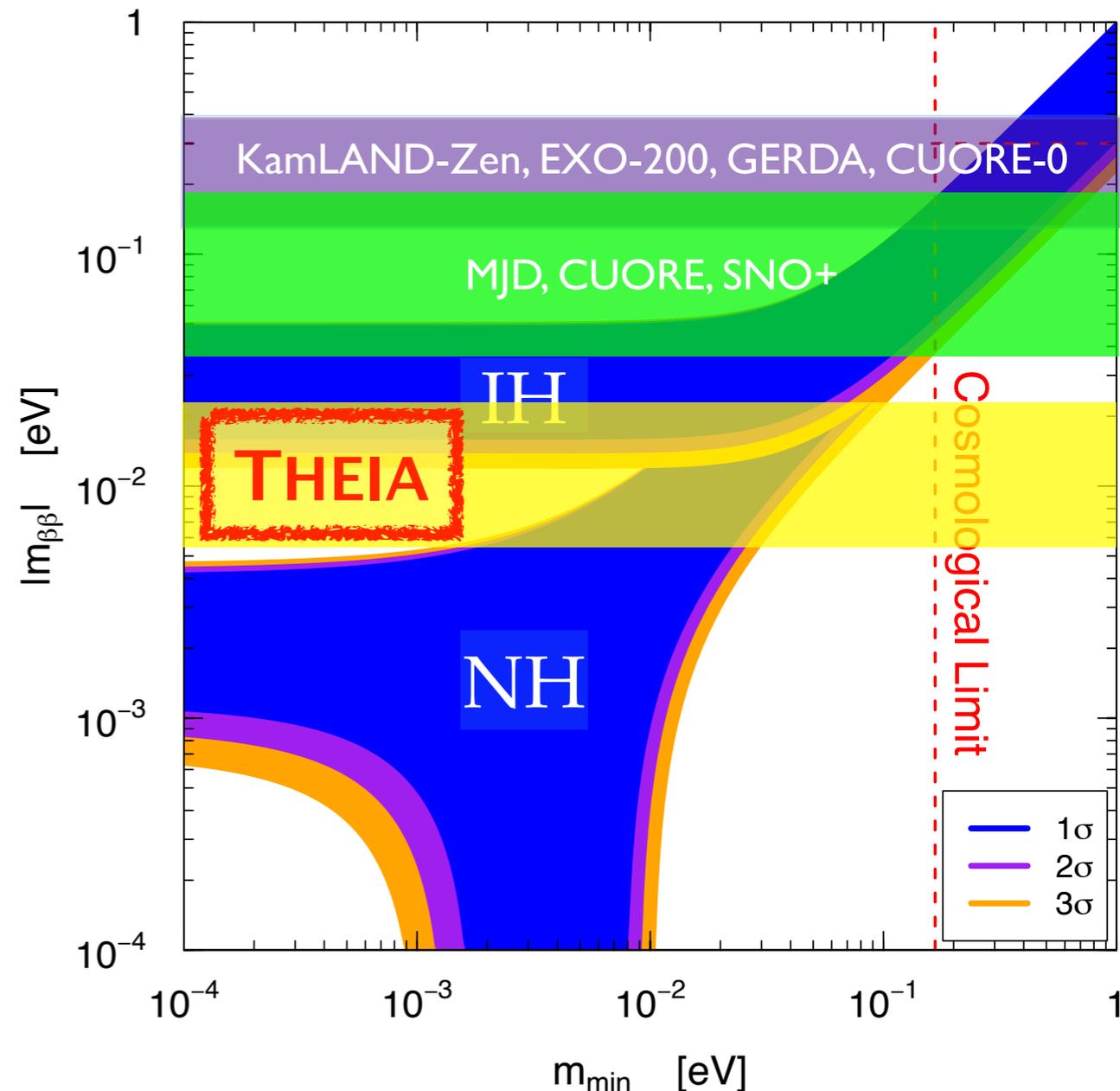
Projected backgrounds in SNO+, 0.5% ^{nat}Te



SNO+ collaboration

- 50kt detector
- 50% reduction of ⁸B
- Particle ID / coincidence tags for int r/a
- R_{fit} > 5.5m from PMTs (30kt fid)

**m_{ββ} = 6.7 meV (1% Te),
 5.5 meV (2% ^{enr}Xe)
 90% CL in 5 yrs**



S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

THEIA Solar Sensitivity

1996, W.C. Haxton: isotope loading for CC interaction (water)

“Salty water Cherenkov detectors” W.C. Haxton PRL 76 (1996) 10

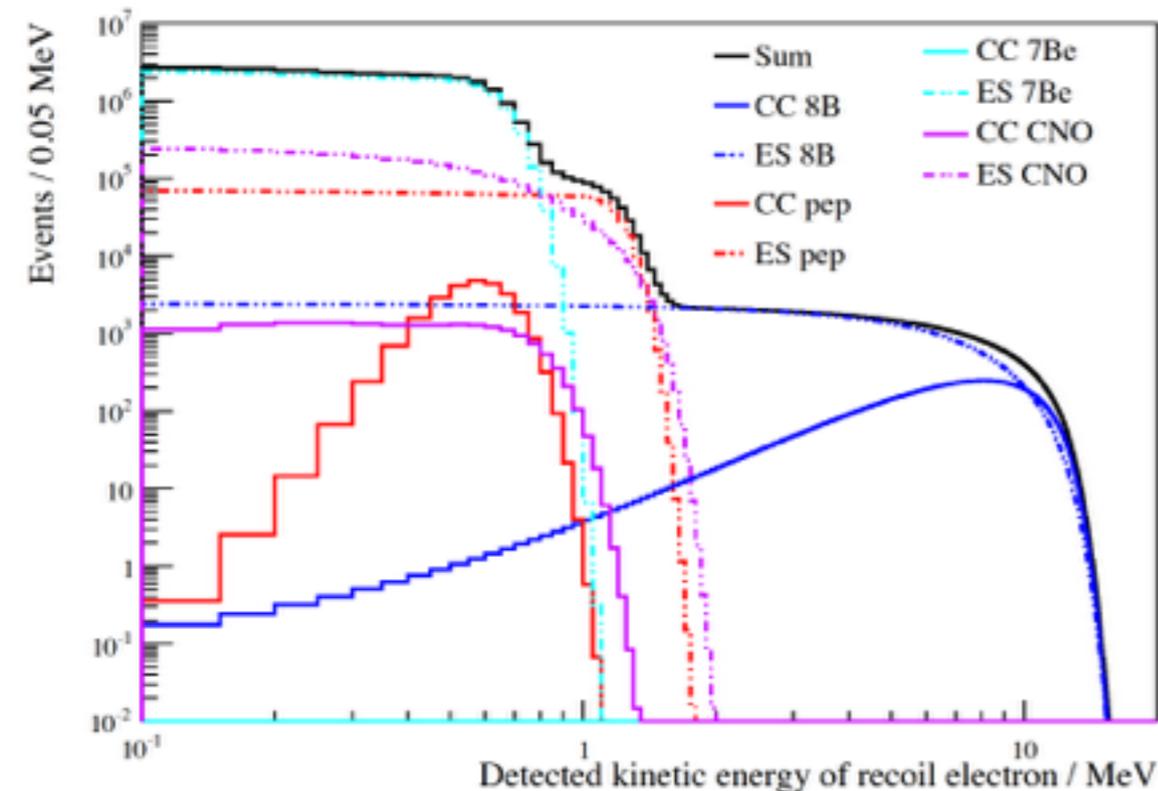
2000s, M. Yeh *et al.*: water-based liquid scintillator

Nucl. Inst. & Meth. A660 51 (2011)

CC detection in WbLS: high-precision spectral measurement to low energy!

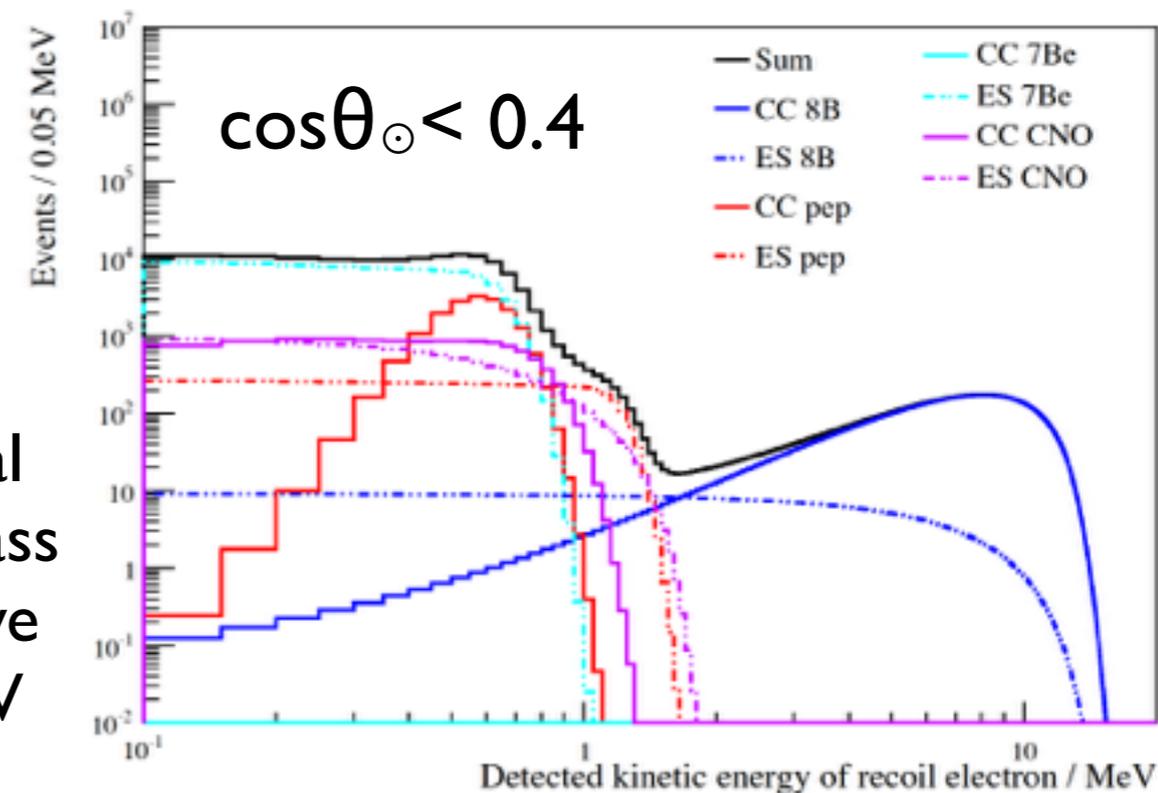
⇒ search for new physics, neutrino-matter interactions, solar metallicity

Unprecedented low-energy statistics (ES)



30kt fiducial
1% ⁷Li by mass
Conservative
100 pe/MeV

Spectral Sensitivity (CC)



Enabled by use of WbLS (⁷Li, CC)

Similar to LENA — Astropart. Phys. 35 (2011) 685-732
+ directionality from Cherenkov

CHESS:

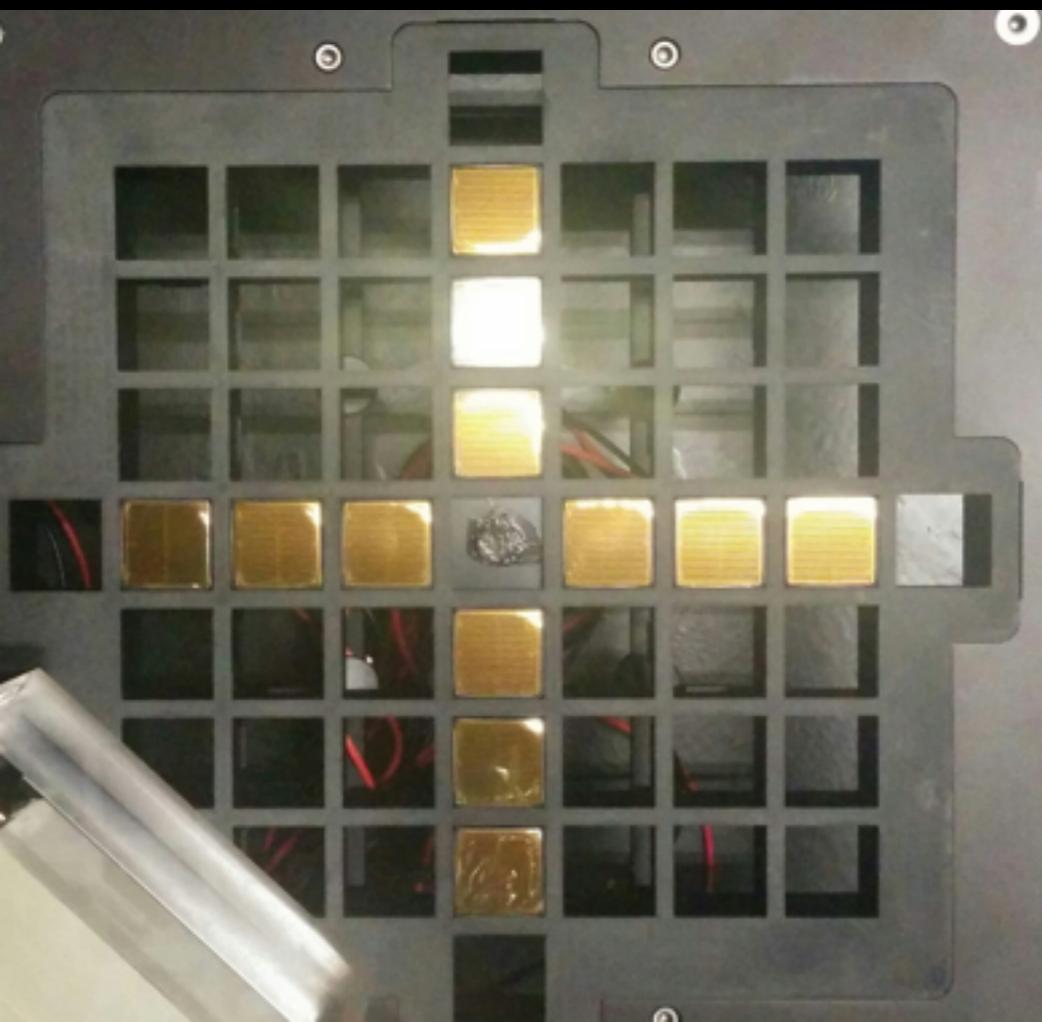
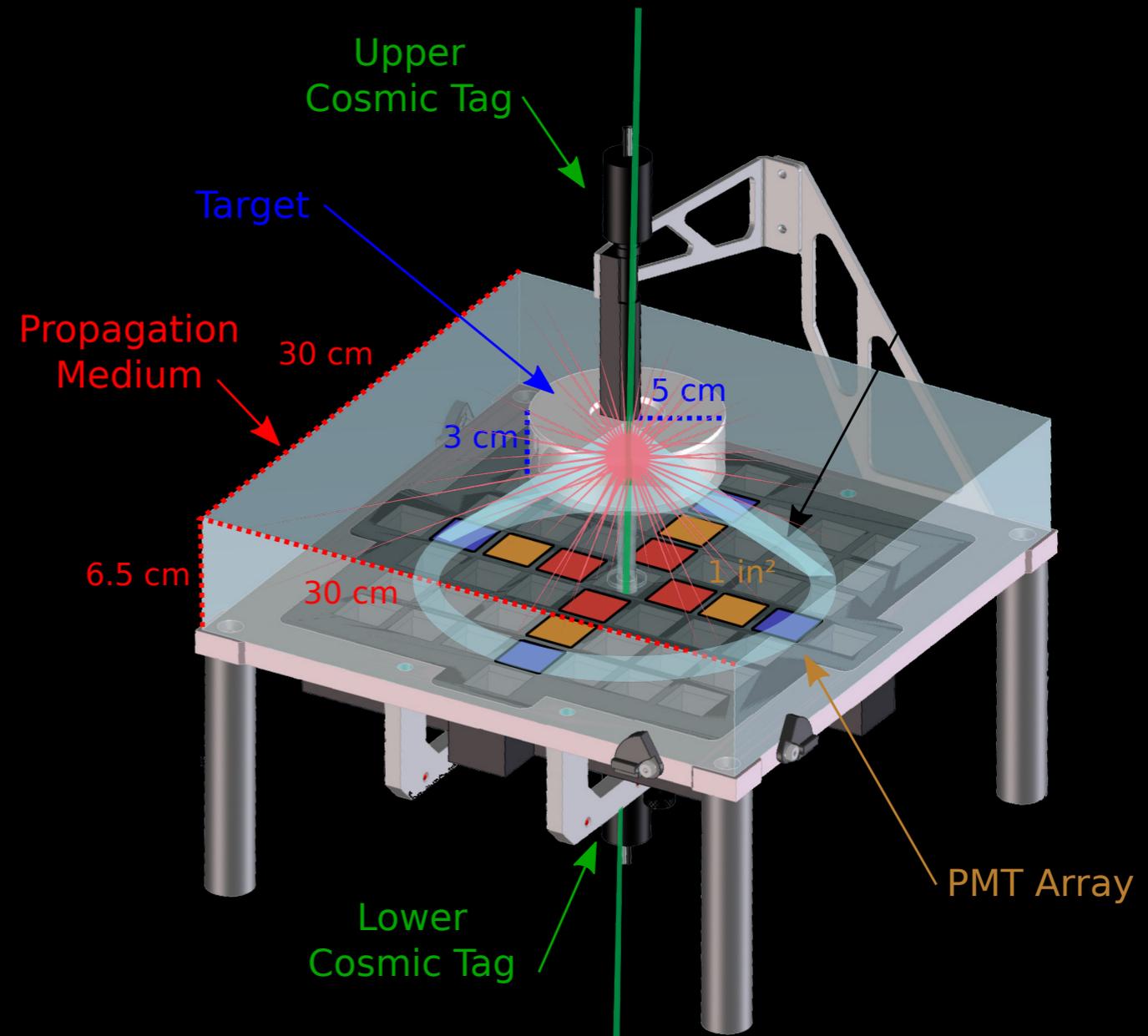
CHerenkov-Scintillation Separation

Select vertical cosmic muon events

Image Cherenkov ring in Q and T
on fast-PMT array

Detector resolution: 338 ± 12 ps

Allows charge- and time-based separation



12 1-inch H11934 PMTs (300ps FWHM, 42% QE)

CAEN V1742 (5GHz)

675 samples (135ns window)

CAEN V1730 (500MHz)

CHESS:

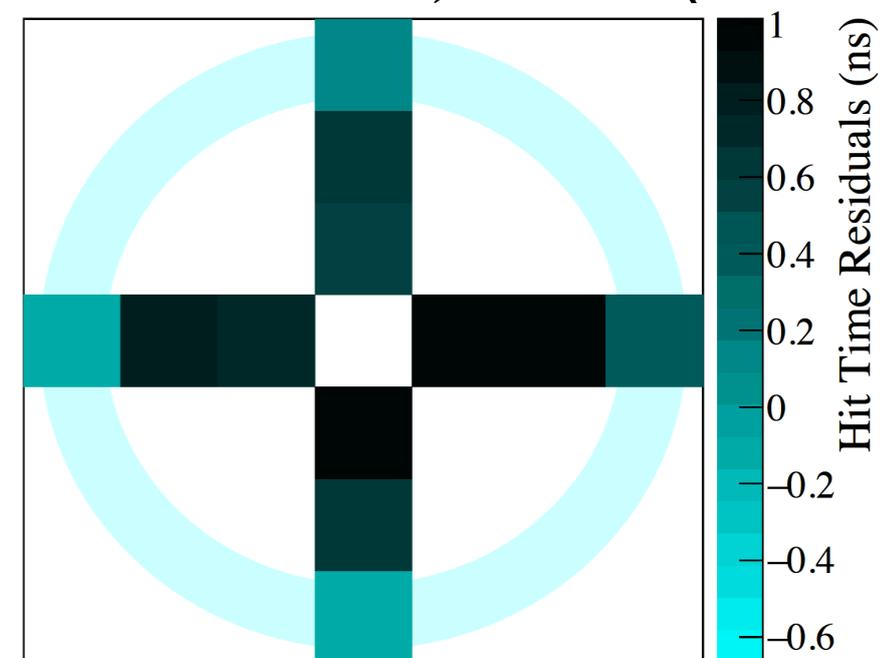
Orebi Gann research group
Supported by LBNL LDRD (FY '15-16)

CHerenkov-Scintillation Separation

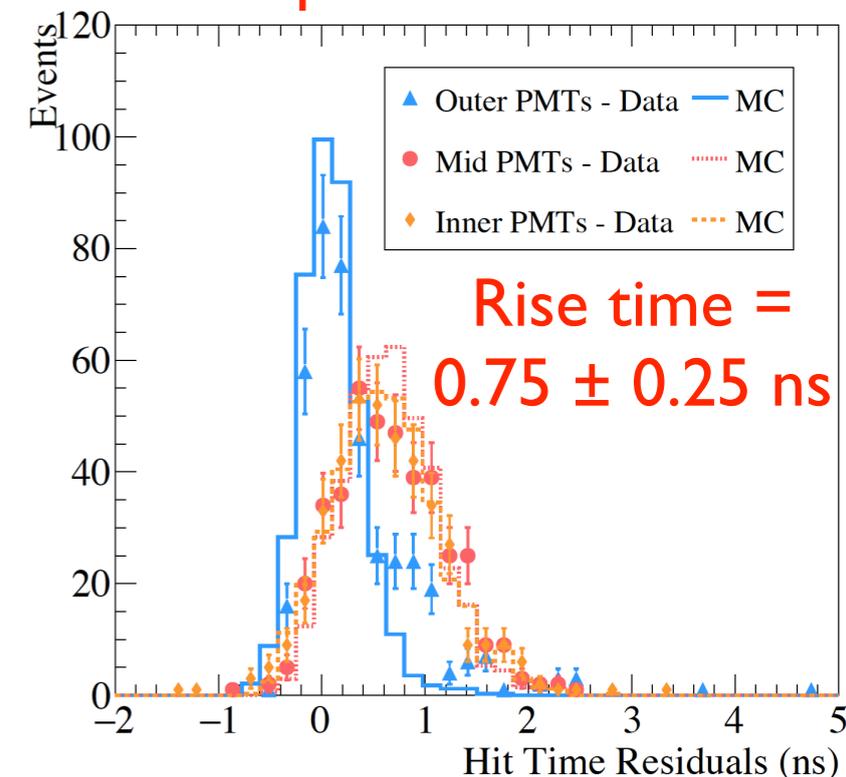
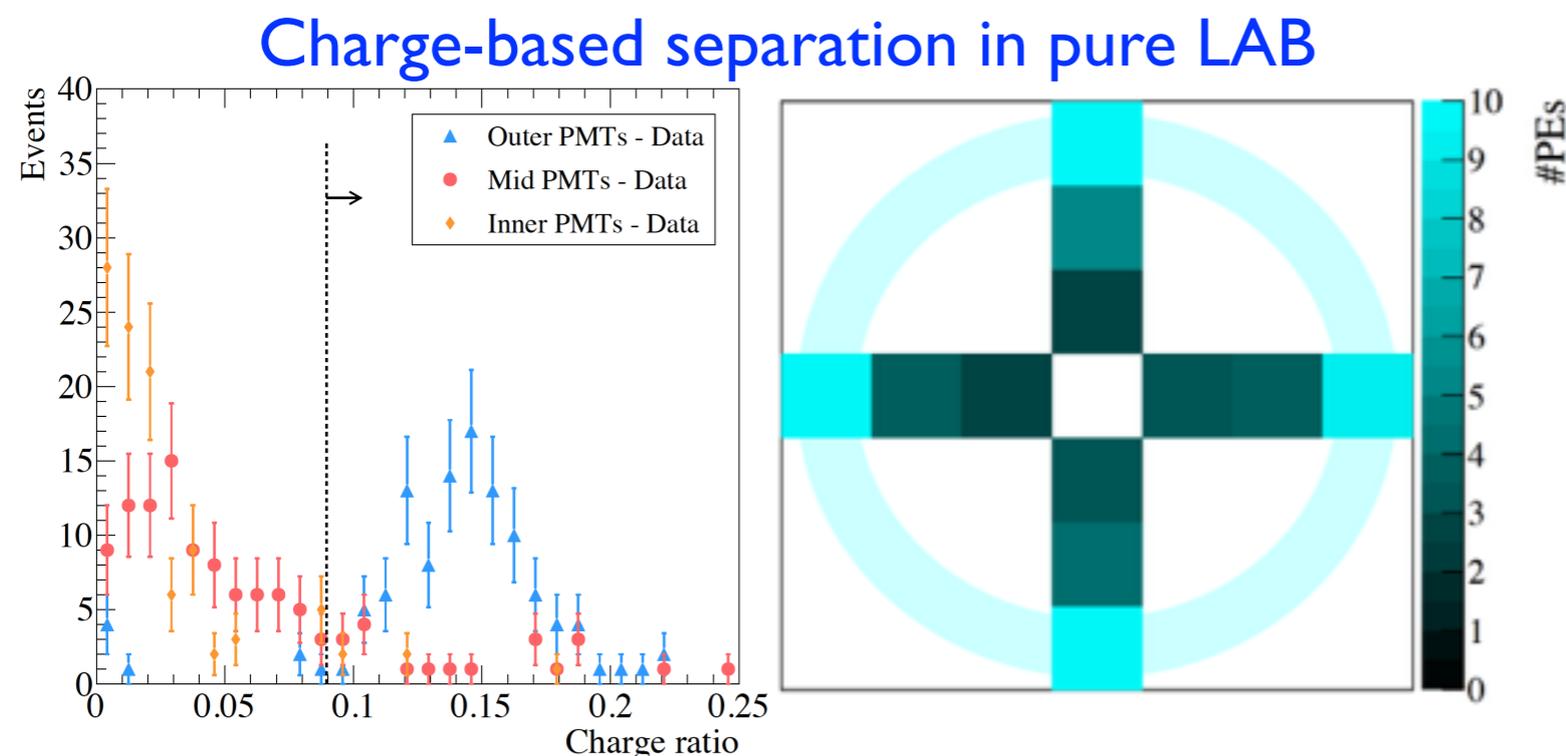
arXiv:1610.02011, arXiv: 1610.02029
Submitted to PRC, PRL

See dedicated talks at DNP, FROST (Oct '16)

	LAB Time- based	LAB Charge- based	LAB/PPO Time- based	LAB/PPO Charge- based
Cherenkov detection efficiency	$83 \pm 3 \%$	$96 \pm 2 \%$	$70 \pm 3 \%$	$63 \pm 8 \%$
Scintillation contamination	$11 \pm 1 \%$	$6 \pm 3 \%$	$36 \pm 5 \%$	$38 \pm 4 \%$



Time-based separation in LAB/PPO



Full simulation includes detailed geometry, DAQ effects (TTS, pulse shapes, electronics noise...)

CHESS: Future plans

- Full study of Cher / scint separation in WbLS
 - Quantify impact of LS fraction
 - Quantify impact of fluor type & fraction
 - Quantify impact of isotope loading
- Expand setup to include additional measurements
 - Light yield
 - Scintillation timing profile
 - Particle identification capabilities (α - β , β - γ separation)
- Optimize THEIA target using output from these results
 - Physics sensitivity: solar, DSNB, NLDBD

Summary

- SNO+ :
 - potential for world-leading $m_{\beta\beta}$
 - broad physics program
 - leadership role
 - calibration, detector, physics analysis

- SNO :
 - existing data set offers many opportunities
 - leadership role
 - spearheading multiple new physics analyses

- THEIA :
 - potentially revolutionary technology
 - unique flexibility to adapt to new scientific directions
 - leadership role & critical R&D effort